National Aeronautics and Space Administration

Physics of the Cosmos Program Annual Technology Report

Physics of the Cosmos
Program Office
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EXECUTIVE SUMMARY

This Program Annual Technology Report (PATR) is the annual summary of the technology development activities in support of the Physics of the Cosmos (PCOS) Program for the fiscal year (FY) 2011. The PCOS Program Office resides at the NASA Goddard Space Flight Center (GSFC) and serves as the implementation arm for the Astrophysics Division at Headquarters (HQ) for PCOS Program related matters. The PCOS PATR describes the state of the Program's technology management activities and summarizes the Program's technology development status for the prior year.

The PATR contains the community-provided technology needs for PCOS-related science and the Technology Management Board's (TMB) prioritization of the technology needs and investment recommendations. This information will be referenced by the Program over the upcoming year, as the calls for technology development proposals are drafted and investment decisions made. Comments from the community are invited at every stage, and specific technology needs inputs are requested at the start of each summer to begin the prioritization cycle again. This process improves the transparency and relevance of technology investments, provides the community a voice in the process, ensures open competition for funding, and leverages the technology investments of external organizations by defining a need and a customer.

Goals for the PCOS Program envisioned by the National Research Council's (NRC) "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH) Decadal Survey report include science missions and technology development for dark energy, gravitational waves, X-ray astronomy, and inflation. Having lost three missions in formulation in 2011, the PCOS Program shifted its efforts to administering the operational missions and managing mission concept and technology studies. These studies currently include gravitational wave and X-ray astronomy mission concepts.

Recognizing that the above mentioned goals and missions present numerous technological challenges with varying time horizons, the NWNH report recommends that NASA maintain support for the development of technologies that feed into these projects. It is the goal of the PCOS Program to shepherd all of these technologies to the point at which they can transition into project technology plans. In so doing, these technologies can serve as the foundation for robust mission concepts for review by the community such that the scientific relevance of proposed missions will be prioritized in subsequent strategic planning.

The PCOS Program and the community have a robust technology development history to draw from for this inaugural annual technology report. Responsibility for generating this PATR rests with the Advanced Concepts and Technology Office (ACTO), within the Program Office (PO). The ACTO has captured the activities of the past year to acknowledge important prior work and to describe the basis for the activities for the coming year.

The PCOS Program Office has been established, and the ACTO is fully staffed, to support the technology development activities for future PCOS missions. The initial mission development portfolio includes gravitational wave mission concepts and X-ray astronomy mission concepts.

The NWNH provides guidance for establishing the appropriate content for this newly established program. The first step in the technology development process is to identify the technologies required to support PCOS science missions. This process involves the scientific and technological community that is defining the future missions and the Physics of the Cosmos Program Analysis Group (PhysPAG). Once these technology needs are identified, they are prioritized by the TMB, based on a set of evaluation criteria that reflects the goals of the Program in the current programmatic environment. The output is a list of technology areas in which needs and their relative importance are described. This output can then be used by the PCOS Program to solicit ideas for development and to inform the selection and make investment decisions. Relative importance has been defined to mean the ranking of a particular technology with respect to a set of prioritization criteria. These criteria are described in the report, and they are intended to assess relevance from the scientific, technical, and programmatic perspectives.

The technology needs prioritization process was completed, and the results are categorized into five groups, labeled Priority 1 to 5, in order of descending priority. These groups describe the relative importance of the technologies to the PCOS science objectives and the urgency of the need. Technologies in the higher priority group have higher relative priority, higher technology "pull," and more near-term needs than the subsequent priority groups.

Multiple factors are considered in any selection process, and the priority groups defined in this PATR comprise only one. As all factors are considered, the Board recommends that the PCOS Program seek to balance the technology investments across the multiple PCOS science objectives and anticipated missions. Finally, the Board is cognizant that investment decisions will be made within a broader context and that other factors at the time of selection may affect these decisions.

The technology development planning for the Program Office is complete and it is ready to provide the leadership required to advance the technologies for the missions under its purview. As the FY12 activities progress, these plans may be adjusted as necessary to match programmatic needs. The Program Office remains committed to providing a transparent, merit-based, and balanced process for supporting the technologies needed to help ensure the success of the Physics of the Cosmos Program.

SECTION 1.0 PROGRAM OVERVIEW

Physics of the Cosmos science addresses the fundamental physical laws and properties of the universe. It probes the validity of Einstein's General Theory of Relativity and the nature of spacetime, the behavior of matter and energy in extreme environments, the cosmological parameters governing inflation and the evolution of the universe, the nature of dark matter and dark energy, the origin and acceleration of cosmic rays, and the mass and properties of the neutrino. 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.

In 2009, under the direction of the Astrophysics Division of the Science Mission Directorate at NASA Headquarters, NASA acknowledged this unique science and its continued importance to Astrophysics by officially formulating the Physics of the Cosmos (PCOS) Program. In May 2011, the PCOS Program Acceptance Review was conducted, and on August 3, 2011, the Agency Program Management Council authorized the PCOS Program to proceed into the program implementation phase.

The PCOS Program Office is located at the NASA Goddard Space Center. A primary function of the Program Office during the implementation phase is to develop and administer an aggressive technology program. In order to achieve this end, an Advanced Concepts and Technology Office (ACTO) has been chartered to facilitate, manage, and implement the technology policies of both the PCOS Program and the Cosmic Origins (COR) Program. The goal is to coordinate the infusion of technology into PCOS and COR 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.

ACTO 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 is the first comprehensive document detailing the technologies currently being pursued and supported by PCOS SR&T. It also outlines a view, as of late 2011, of the PCOS roadmap for future technology needs.

1.1 Background

The PCOS Program encompasses multiple science missions aimed at meeting Program objectives, each with unique science capabilities. The program was established to integrate those missions into a cohesive effort that enables each project within the Program to build upon the technological and scientific legacy of both its contemporaries and predecessors. At Program inception, the following operating and future projects were placed within the Program to be shepherded commonly in support of "Physics of the Cosmos" Science goals. Each project operates independently to achieve its unique set of mission objectives, which contribute to the overall Program objectives. The initial PCOS missions were:

Operating Missions:

- *Chandra*
- X-ray Multi-mirror Mission (*XMM*) – *Newton*
- *Fermi Gamma-ray Space Telescope*
- *Planck*

Future Missions:

- *Joint Dark Energy Mission* (JDEM)
- *International X-ray Observatory* (IXO)
- *Laser Interferometer Space Antenna* (LISA)
- *Inflation Probe*
- *Black Hole Finder Probe*

Since the Program began formulation in 2009, the portfolio of future PCOS missions has changed dramatically. Starting with the release of the NRC's NWNH report, and cumulating with the current fiscal constraints, the PCOS Program focus has necessarily shifted from mission development to technology studies.

The NWNH report highly valued the planned PCOS science missions for dark energy, gravitational waves, and X-Ray astronomy. The committee proposed, and ranked first, a mission called *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. While dark energy is PCOS science, for programmatic reasons, NASA chose to administer WFIRST through the Exoplanet Program Office. The committee ranked LISA and IXO the third and fourth priorities for large space-based investments.

For a brief period in 2010 and early 2011, NASA explored a minority role in the ESA-lead *Euclid* mission. *Euclid* is also a dark energy mission. Its science objectives are similar to those of JDEM and, now, WFIRST. In February 2011, following recommendations of the NRC's "Report of the Panel on Implementing the New Worlds, New Horizons Decadal Survey," NASA decided not to participate in *Euclid* and, instead, to invest funds in Decadal-ranked missions.

In March 2011, the European Space Agency (ESA) announced that, due to the lower ranking of the joint NASA/ESA missions in both the Astrophysics and Planetary Decadal surveys and the constraints on the NASA budget, it would no longer pursue the LISA, IXO, and Laplace missions, which were developed jointly with NASA. Instead, it would investigate lower-cost ESA-led mission concepts, the *New Gravitational-wave Observatory* (NGO) and the *Advanced Telescope for High-Energy Astrophysics* (ATHENA), which replace LISA and IXO. If either of these missions is selected in the ESA Cosmic Visions process, NASA may play a minority role.

With the loss of three missions in development, the PCOS Program has shifted its efforts to administering the operational missions and managing mission concept and technology studies. These studies include:

- gravitational wave mission concepts
- X-ray astronomy mission concepts

1.2 PCOS Program Technology Development

The PCOS Program has taken over responsibility for managing the development of the core technologies for gravitational wave and X-ray astronomy missions. For the Fiscal Year 2012, the near-term driving objective is to maintain progress in those technologies that either have a clear connection to a possible contribution to the ESA L-class missions, ATHENA or NGO, and/or are key enabling technologies for a future U.S.-led mission.

The PCOS SR&T funds a variety of technology developments that are determined to be necessary for the advancement of PCOS science missions. Specifically, the PCOS Program Office inherits the mantle of the NWNH via its adoption of the prioritized complement of missions and activities to advance the set of PCOS science priorities. This strategic vision comes principally from NWNH.

The PCOS/COR 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 (Figure 1) illustrates the annual cycle by which this is achieved. Starting at the left, science needs and requisite technologies are derived from the current astrophysics community, and are presented into the NASA advisory chain. The PCOS Program Office is aware of these science needs independent of the PhysPAG, as all such presentations and deliberations are public.

The PhysPAG provides analyses through the Federal Advisory Committee Act (FACA)-mandated process. Meanwhile, the PCOS Program Office convenes its Technology Management Board (TMB), which prioritizes the technologies and publishes them annually in this PATR. The

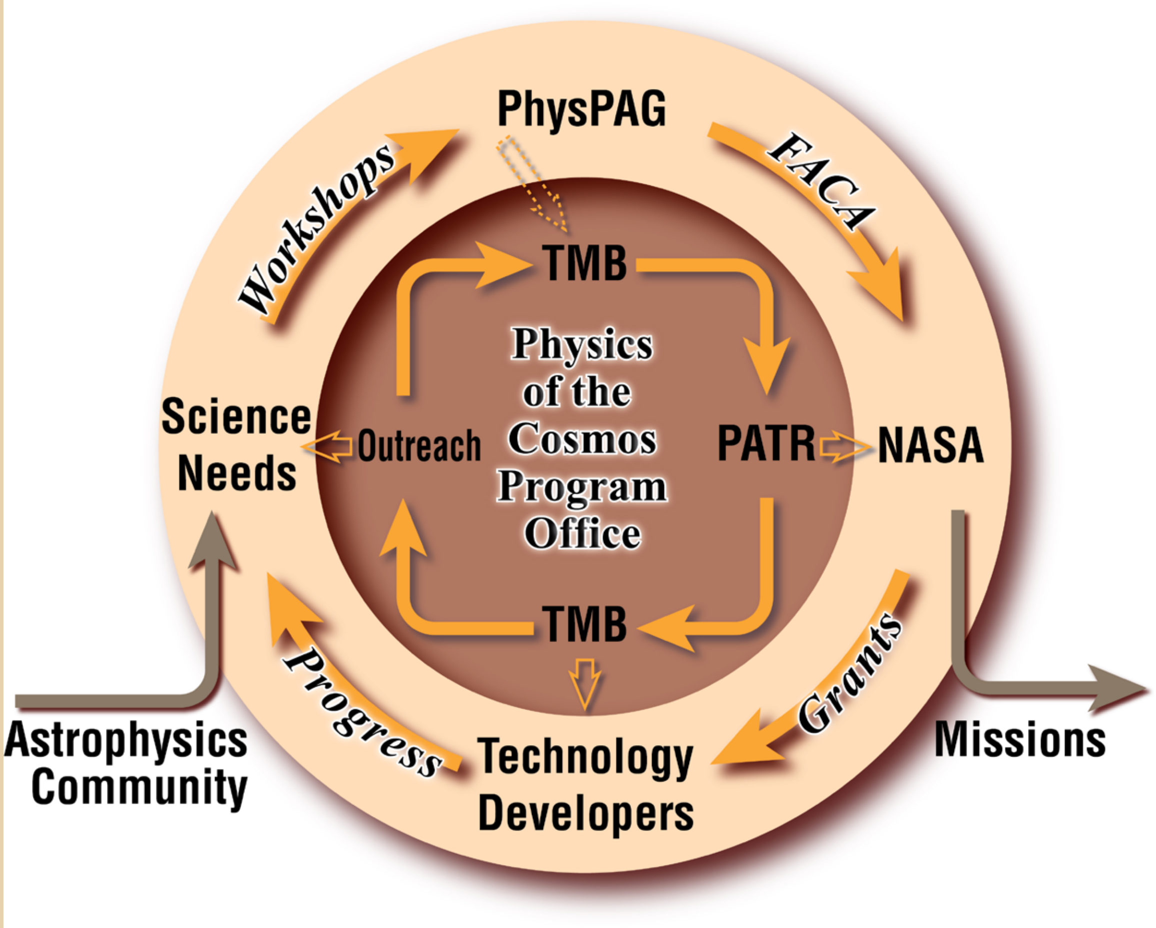

Figure 1. *The PCOS "Technology Turntable" illustrates the annual process by which science needs and their requisite technologies are indentified, prioritized, and matured.*

TMB recommends these priorities to NASA HQ, which solicits proposals for technology development. Grants are awarded to technology developers, who submit annual reports that are reviewed by the TMB. Technological progress also changes the landscape of the requirements for the science needs, and so this process is repeated annually to ensure continued currency of the priorities.

The PCOS PATR plays an important role in this process. It will describe the status of all technologies funded through PCOS SR&T, capture technology needs as articulated by the science community, and recommend a prioritized list of technologies for future funding. The PCOS PATR will be an open and available source for the public, academia, industry, and the government to learn about the status of those missions and enabling technologies required to fulfill the PCOS Program science objectives.

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

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

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. This prioritization provides crucial direction for the merit-based selection of technology development investment. This report, the annual PCOS PATR, is the means of disseminating this information publicly.

SECTION 2.0 TECHNOLOGY STATUS

Introduction

This section describes the current status, progress over the past year, and planned development activities for all the technologies that were supported by PCOS SR&T funding in FY11. These include technologies developed for LISA, IXO, and *Euclid*. The PCOS Program supported each of these technologies in FY11 for the purpose of advancing the development of these specific flight projects. As noted in Section 1, NASA's participation in each of these projects has been terminated. However, for completeness and to capture the important development that was performed to enable potential future gravitational wave mission, X-ray mission, and WFIRST, the technology development statuses are included in this section. Table 1 lists funded enabling technologies for the missions.

Section	Funded Technologies for Missions
2.1	LISA/Gravitational Wave Technology
2.1.1	Colloidal Micronewton Thrusters
2.1.2	Phase Measurement System (PMS) Technology
2.1.3	Telescope Spacer Technology
2.1.4	Laser Component Technology
2.1.5	Laser System Architecture Technology
2.1.6	Optical Assembly Tracking Mechanism Technology
2.1.7	Custom Photoreceiver Technology
2.2	Euclid/WFIRST Technology
2.3	IXO/X-ray Technology
2.3.1	X-ray Telescope: Slumped Glass Mirror Technology
2.3.2	Critical Angle Transmission X-ray Grating Spectrometer (CAT XGS)
2.3.3	Off-plane X-ray Grating Spectrometer (OP-XGS)
2.3.4	X-ray Microcalorimiter Spectrometer (XMS) Technology

Table 1. *FY11 Funded Technologies*

It should be noted that the technology development that was funded by PCOS for the *Euclid* project was folded into the development for the WFIRST after NASA decided not to participate on *Euclid*. So while WFIRST is not a PCOS project, this technology development is described here because it was supported in FY11 by PCOS.

The information contained in this section provides technology overviews and is not intended to provide technical detail for flight implementation. The specific technology readiness levels (TRL) for each technology have been omitted by design, because the TRLs claimed for each technology have yet to be vetted by the PCOS Program Technology Management Board (TMB). The PCOS Program Office intends to include applicable TRLs for each technology in the subsequent year's PATR, as TRLs for a technology is reviewed and concurred by the TMB.

The PCOS Program evaluated targeted technologies under development for the LISA and IXO projects to assess their strategic applicability to the PCOS Program. Previously, while both LISA and IXO were projects, the LISA and IXO technology developers were instructed not to apply to HQ SAT calls because their technology development funding had been allocated via respective projects. However, with the termination of these projects in early spring, the funding for FY12 was in flux. The Program Office convened special Technology Management Boards (TMB) to address FY12 funding for these projects.

The TMB evaluated these targeted technologies selected for funding in FY12 based on the following criteria: (1) Technology must either have a clear connection to a possible United States contribution to the European Space Agency L-class missions or be a key enabling technology for a possible U.S.-led mission, or both; (2) Work planned for FY12 is reasonable and significant, and the end product for the development year is clearly defined; (3) Proposed budget is adequate and required. The table below provides information for the technologies approved for development in FY 12.

Proposed Work	PI	Institution
X-ray mission mirrors: Develop glass mirror segment fabrication and mounting techniques toward demonstration of TRL 5	W. Zhang	Goddard Space Flight Center
X-ray mission micro-calorimeter: Develop 32 x 32 arrays that incorporate ATHENA "pitch" and 3 x 16 readout for demonstration of TRL 5	C. Kilbourne	Goddard Space Flight Center
Gravitational wave mission telescope: Establish telescope design that meets pathlength stability and wavefront error requirements for NGO; demonstrate optical and scattered light performance for telescope	J. Livas	Goddard Space Flight Center
Gravitational wave mission phasemeter: Design and demonstrate modifications to phasemeter that support relaxation of LISA's requirements on laser noise, orbital parameters, and received optical power; assemble and test analog signal chain pre-amp board	W. Klipstein	Jet Propulsion Laboratory

Table 2. *PCOS Targeted Program Awards*

Selection of proposals for funding under the PCOS 2010 Strategic Astrophysics Technology (SAT) solicitation was made based on the following factors: (1) the overall scientific and technical merit of the proposal; (2) the programmatic relevance of the proposed work; and (3) the cost reasonableness of the proposed work. These technologies have recently been selected for funding and have not yet begun serious work, and hence each project's status is not presented here. Their progress in the first year will appear in this section in the 2012 PATR. The table below provides information for the technologies approved for development in FY 12.

Title	PI	Institution
Development of Fabrication Process for Critical-Angle X-ray Transmission Gratings	M. Schattenburg	Massachusetts Institute of Technology
Antenna-Coupled Superconducting Detectors for Cosmic Microwave Background Polarimetry	J. Bock	Jet Propulsion Laboratory
Directly-Deposited Blocking Filters for Imaging X-ray Detectors: Technology Development for the International X-ray Observatory	M. Bautz	Massachusetts Institute of Technology
Off-plane Grating Arrays for Future Missions	R. McEntaffer	University of Iowa
Development of Moderate Angular Resolution Full Shell Electroplated Metal Grazing Incidence X-ray Optics	P. Reid	Smithsonian Astrophysical Observatory

Table 3. *SAT/ Technology Development for Physics of the Cosmos (TPCOS) Awards*

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2.1 LISA/Gravitational Wave Technology

Prepared by: Jeff Livas (NASA/GSFC), William Klipstein (JPL),
John Ziemer (JPL), Jordan Camp (NASA/GSFC), and
J. Ira Thorpe (NASA/GSFC)

Gravitational Wave Measurement System Summary

There are two essential parts to the measurement system for space-based gravitational waves: a Disturbance Reduction System (DRS), which is responsible for isolating the test masses from all extraneous forces, and an Interferometric Measurement System (IMS), which is responsible for measuring the relative displacements between pairs of test masses with high precision.

Technology development for space-based gravitational detectors in the U.S. over the past year has focused on technologies for both essential measurement subsystems.

Physical effects of a gravitational wave

The fundamental physical effect of a passing gravitational wave is to create a strain in spacetime in a plane perpendicular to the direction of propagation of the wave. The strain distorts spacetime by stretching it along one axis and simultaneously shrinking it along a perpendicular axis, much as a rubber band reacts to being stretched.

Gravitational waves have two polarizations, just as with electromagnetic waves, and the detailed physics of the astrophysical sources are encoded in the variations of these polarizations. Figure 2 shows the response of a ring of test masses (analogous to a ring of test charges for electromagnetism) to a passing gravitational wave. The classic *Laser Interferometric Space Antenna* (LISA) concept detector is a three-satellite constellation that samples this ring. (The former joint NASA/ESA mission, known as the LISA mission, had implemented this LISA concept.)

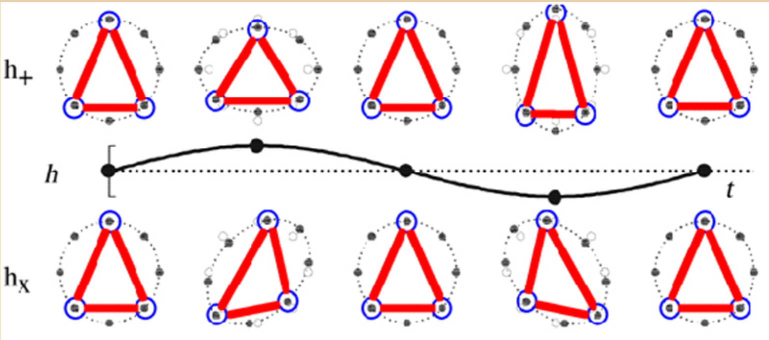


Figure 2. *The fundamental physical effect of a gravitational wave is to create a strain in spacetime. Shown here is the response of a ring of test masses (or the LISA configuration of an equilateral triangle of three spacecraft) to a gravitational wave traveling into the paper for each of the two polarizations, h_+ and $h_\times$.*

The classic LISA concept orbits are independent Keplerian orbits around the sun, with the three spacecraft aligned as a triangle in a plane inclined at 60 degrees to the ecliptic. The orbits are phased such that the separations between the spacecraft remain constant to within plus or minus 1% for at least five years. The spacecraft are eventually pulled apart by the action of other planetary bodies. Since each orbit is independent, there is no active control or maintenance of the constellation required and, in particular, no propellant for station keeping.

Disturbance Reduction System (DRS)

The Disturbance Reduction System uses precision drag-free control to sense the position of the test mass with respect to the spacecraft and then move the spacecraft around to keep it centered on the proof mass. The purpose of the DRS is to reduce the residual forces on the test mass in the gravitational wave measurement band so that gravitational forces (which, of course, cannot be shielded) dominate the residual acceleration budget.

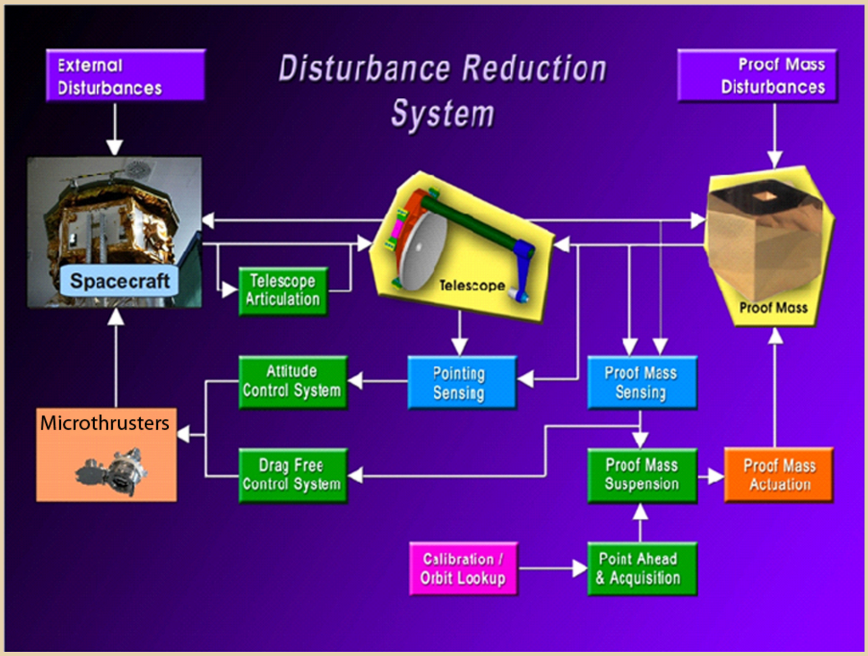


Figure 3. *The Disturbance Reduction System (DRS) consists of three main elements: 1) a gravitational reference sensor (GRS), which contains the test mass; 2) micronewton thrusters, and; 3) control laws (DFACS).*

There are three main components of the DRS:

- a test, or proof, mass, as part of the gravitational reference sensor (GRS)
- a micronewton thruster actuator
- a set of control laws that tie the sensor and actuator together as a system

The control laws are known as the Drag-Free and Attitude Control System (DFACS). Figure 3 shows a block diagram of the complete DRS.

In FY11, DRS technology development at NASA has focused on the micronewton thruster. The Euopean Space Agency (ESA) has developed a GRS for the *LISA Pathfinder* (LPF) mission, and both NASA and ESA have already developed a set of control laws. ESA is pursuing a Field Emission Electric Propulsion (FEEP) thruster, and NASA is developing a colloidal micronewton thruster (CMNT). The LPF Project is bringing along cold gas and micro-RIT thrusters as a backup. The CMNTs are the only thruster that has advanced to flight readiness for LPF. The European Cesium Field Emission Electric Propulsion (Cs-FEEP) technology has had intermittent technical issues. Although the difficulty with oversupply of propellant was recently resolved by reducing the slit width to 0.3 μm from 1.0 μm, only one prototype has successfully demonstrated basic performance.

Interferometric Measurement System (IMS)

The Interferometric Measurement System (IMS) measures the distance between pairs of test masses on different spacecraft. There is a separate measurement for each direction, so there are two optical measurement subsystems assemblies, or links, per pair of test masses, or arms, for a total of three arms, or six links, for the LISA concept baseline.

Figure 4a shows a view of the complete observatory from a point above the plane of the triangle showing the three individual spacecraft connected by three arms and six links. Each spacecraft has two complete optical assemblies, which consist of a gravitational reference sensor (GRS) containing the proof mass, an optical bench, and a telescope. These optical assemblies point down each arm and form the transmitter for that arm in one direction and a receiver for that arm in the other direction. Note that the drawing is not to scale as the spacecraft are ~2.7 m in diameter and the spacing between spacecraft is 5×10^9 m.

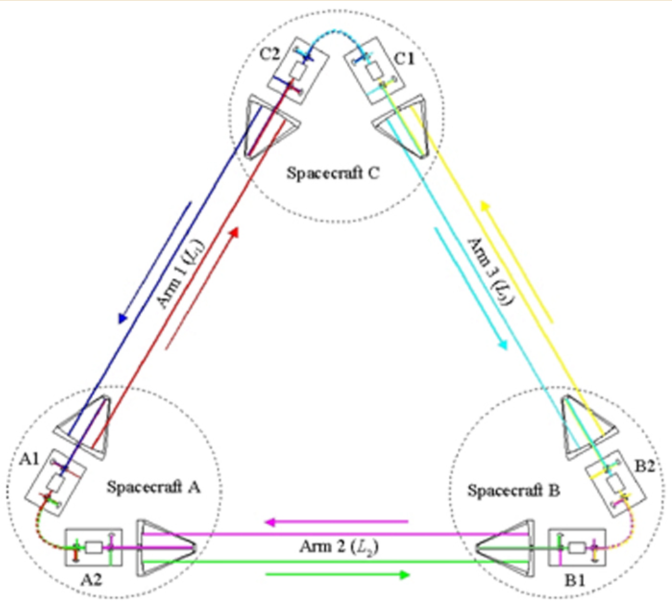


Figure 4a. *The interferometric measurement system (IMS) measures the separation between test masses in different spacecraft. The distance is measured separately in each direction between a pair of masses (or "arm"). Each measurement is called a "link" and contains a separate subsystem consisting of a transmit laser, photoreceiver, local oscillator laser, and optical system, including a telescope.*

The optical measurement subsystem assembly consists of a transmit laser subsystem with a nominal output power of 1 W, a quadrant photoreceiver that detects the interference fringes between the transmit laser and a local oscillator laser, a phasemeter that digitizes these fringes and generates the distance estimate, and an optical system. The optical system includes a telescope for collimating the beam between spacecraft and an optical bench for performing the interferometry. Figure 4b shows an optical system from two different vantage points. The telescope has a light shield and faces out into space. Hanging from the back is an optical bench, where the signals are combined to form interference fringes, and then the GRS. The entire assembly is supported on pivots so that the telescope may be pointed toward the far spacecraft and follow changes in the line of sight.

Some technology development or risk-reduction work has been performed on many of the components of the IMS in the past year, including the telescope and the optical assembly tracking system (OATM), and will be described in subsequent sections. Some development work has also been done at the system level on a reliability model.

FY11 Activities

The gravitational wave research projects over the past year aimed at preparing for a flight project. These research projects are classified as either technology development or risk reduction activities, based on the maturity of the underlying concepts. For areas in which the concepts are well developed and relatively mature, the development efforts are classified as risk reduction efforts if the requirements can be met with routine careful engineering and design using established physical principles and methods.

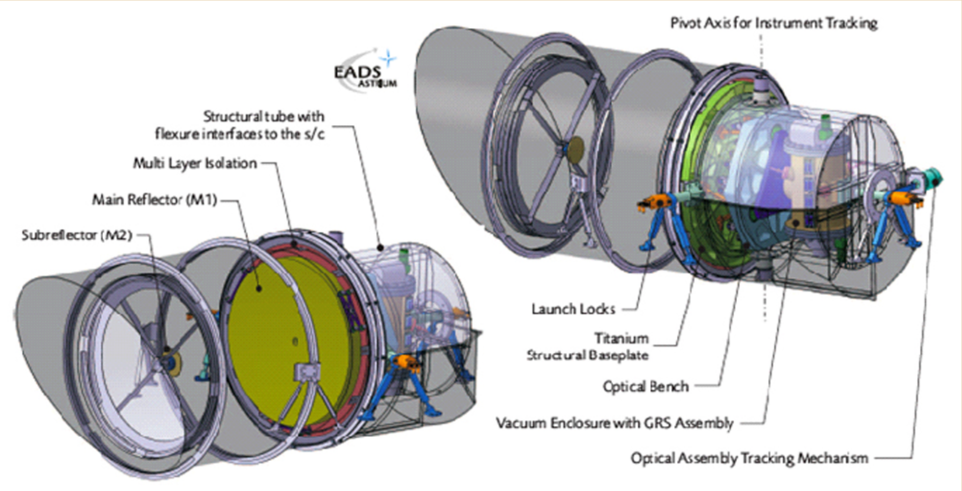


Figure 4b. *The LISA optical system is shown from two different vantage points. There are two complete optical systems per spacecraft—one per arm. Each system is mounted on a vertical pivot to allow the optical axis of the telescope to follow the orbital motion of the spacecraft. Also shown in the picture is the vacuum enclosure for the gravitational reference sensor (GRS) assembly, which is mounted to the optical bench.*

Technology development activities also require good design practices and careful engineering but, in addition, there may be some aspects of the underlying concept that are not well known. In general, technology development activities are multi-year development efforts with long-term milestones and development plans.

For FY11, technology development continued on Colloid Micronewton Thrusters (CMNTs) development and further development of the Phase Measurement System (PMS). The details are described in the next few sections.

Other technology development efforts for FY11 include continuing work on the demonstration of a material and a design for the spacer between the primary and secondary mirrors of a telescope, development and testing of an alternative low-noise quadrant detector, laser subsystem development, the beginnings of a system-level laser system architecture reliability model, and the completion of tests of a candidate actuator for an articulation mechanism for the optical assembly, which includes the telescope, optical bench, and gravitational reference sensor (GRS).

The goal of space-based gravitational wave detectors is to observe astrophysical sources, which are high-energy compact objects interacting in the strong-field gravity limit. Extracting the parameters of these sources is the primary goal, not merely detection, and there is a vigorous effort in parallel with the hardware technology work to develop data analysis techniques for parameter estimation. In general, these efforts are contributed by the scientific community, not funded by the National Space Agencies (NASA or ESA) and, therefore, are outside the scope of this document. Data analysis for gravitational wave detectors is a non-trivial problem, and much progress has been made. Further information on these efforts may be found here: **http://astrogravs.nasa.gov/docs/mldc/**.

2.1.1 Colloid Micronewton Thrusters (CMNTs) Technology

Summary

Micronewton thruster technology development in FY11 concentrated on two main objectives: the development and validation by testing of physics-based models of critical life-limiting and/or failure mechanisms and demonstration of thruster lifetime meeting gravitational wave (formerly LISA) baseline concept requirements.

The physics-based model is extremely important because it allows for accelerated lifetime testing, confidence in the results, and the ability to predict and redesign rapidly as requirements change.

Sufficient lifetime has already been demonstrated to support the LISA Pathfinder mission (~18 months of science operations, equal to or greater than 2,160 hours). In fact, two clusters of four thrusters each were integrated onto the LISA Pathfinder Spacecraft in November 2009. Figure 5 shows a photograph of these flight units before integration.

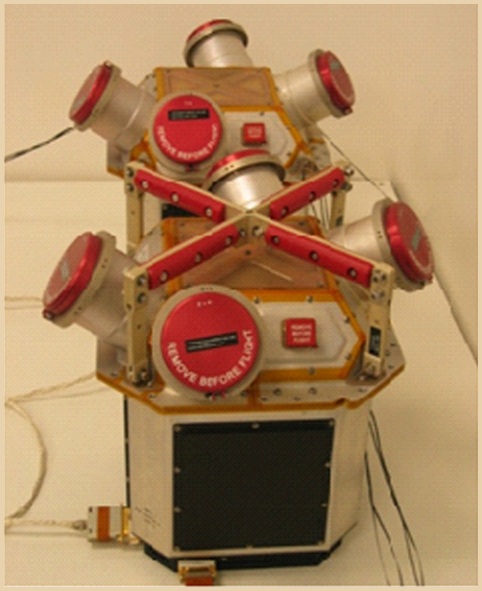


Figure 5. *The micro-colloidal thruster flight model is shown. Pictured are two clusters of four thrusters each that were integrated onto the LISA Pathfinder Spacecraft in November 2009.*

The main remaining effort is to demonstrate a lifetime sufficient for the LISA Baseline mission (five years). As the details of the ESA-only NGO mission become known, it is expected that this goal will be replanned to demonstrate a lifetime that meets NGO requirements, currently baselined for two years of science operation. Figure 6 shows the complete micronewton thruster technology development plan. The current status is shown with a green arrow and includes accelerated life testing and model refinement as the main activities.

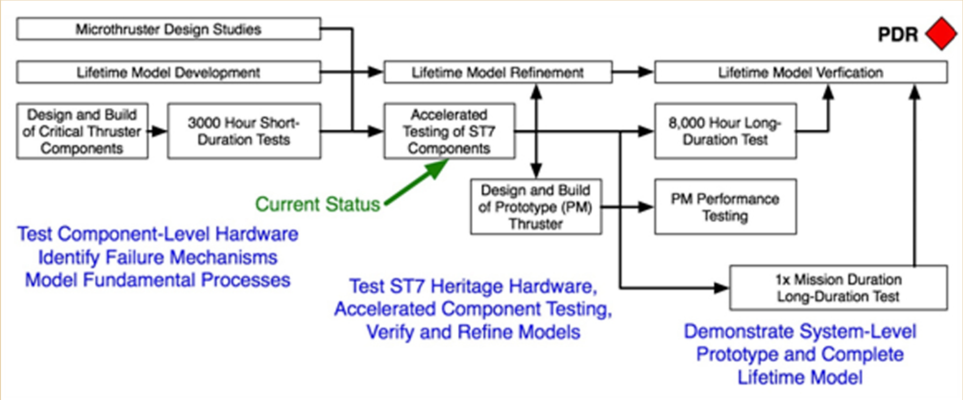
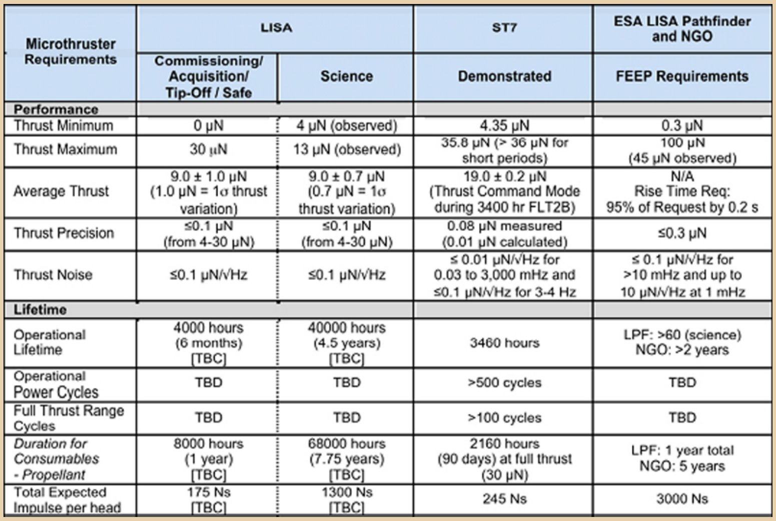


Figure 6. *This technology development plan timeline shows FY11 efforts in the overall context of the complete development plan.*

Technology Description

The micronewton thrusters are the actuators for the Disturbance Reduction System (DRS) that is responsible for isolating the proof mass of the Gravitational Reference Sensor (GRS) from all residual forces except gravity, which cannot be shielded.

Table 4 shows the nominal performance requirements for these thrusters for the LISA baseline concept [CMNT-1], the LISA Pathfinder [CMNT-3] and estimated NGO mission requirements [CMNT-4], and demonstrated performance for the ST7 mission, which is the designation for the U.S. contribution to the *LISA Pathfinder* mission [CMNT-2].



Microthruster Requirements	LISA		ST7	ESA LISA Pathfinder and NGO
	Commissioning/ Acquisition/ Tip-Off / Safe	Science	Demonstrated	FEEP Requirements
Performance				
Thrust Minimum	0 μN	4 μN (observed)	4.35 μN	0.3 μN
Thrust Maximum	30 μN	13 μN (observed)	35.8 μN (> 36 μN for short periods)	100 μN (45 μN observed)
Average Thrust	9.0 ± 1.0 μN (1.0 μN = 1σ thrust variation)	9.0 ± 0.7 μN (0.7 μN = 1σ thrust variation)	19.0 ± 0.2 μN (Thrust Command Mode during 3400 hr FLT2B)	N/A Rise Time Req: 95% of Request by 0.2 s
Thrust Precision	≤0.1 μN (from 4-30 μN)	≤0.1 μN (from 4-30 μN)	0.08 μN measured (0.01 μN calculated)	≤0.3 μN
Thrust Noise	≤0.1 μN/√Hz	≤0.1 μN/√Hz	≤ 0.01 μN/√Hz for 0.03 to 3,000 mHz and ≤0.1 μN/√Hz for 3-4 Hz	≤ 0.1 μN/√Hz for >10 mHz and up to 10 μN/√Hz at 1 mHz
Lifetime				
Operational Lifetime	4000 hours (6 months) [TBC]	40000 hours (4.5 years) [TBC]	3460 hours	LPF: >60 (science) NGO: >2 years
Operational Power Cycles	TBD	TBD	>500 cycles	TBD
Full Thrust Range Cycles	TBD	TBD	>100 cycles	TBD
Duration for Consumables - Propellant	8000 hours (1 year) [TBC]	68000 hours (7.75 years) [TBC]	2160 hours (90 days) at full thrust (30 μN)	LPF: 1 year total NGO: 5 years
Total Expected Impulse per head	175 Ns [TBC]	1300 Ns [TBC]	245 Ns	3000 Ns

Table 4. *The Nominal Microthruster Subsystem Requirements summary for the LISA baseline concept (per a peer review dated December 18, 2009), LISA Pathfinder and preliminary requirements for NGO are shown, as well as the demonstrated performance levels for ST7.*

There are two candidate technologies for micronewton thrusters. ESA has been pursuing a Field Emission Electric Propulsion (FEEP) thruster that is based on either Indium or Cesium ions to generate thrust. NASA's technology, colloidal micronewton thrusters (CMNTs), is conceptually similar to an inkjet printer nozzle. Small droplets of fuel are drawn from a reservoir by capillary action to a needle-shaped nozzle, where they are charged and then accelerated by an electrostatic potential.

Figure 7 shows a photograph of a nozzle in operation and a diagram of the ions and electrostatic potential. Not shown are the fuel reservoir and valves.

The CMNTs appear to be the only candidate thruster technology in the U.S. that can meet LISA baseline concept requirements. Although the FEEP technology under development in Europe can in principle meet the requirements, a development effort of more than approximately 30 years has failed to demonstrate performance sufficient even for LISA Pathfinder. Furthermore, there is no physics-based failure model for the FEEPS that has been extensively validated, as there is with the CMNT thrusters. At this time, therefore, the CMNTs appear to be a unique and critical technology for space-based gravitational-wave detectors.

Status, Progress, and Plan

State of development: The colloid micronewton thruster (CMNTs) flight units for ST7 have been integrated onto LISA Pathfinder for more than a year. Two aspects of this design require further development for the gravitational wave (formerly LISA) baseline concept: larger propellant storage and a five-year lifetime demonstration.

The concept for a larger propellant storage is a gas blow-down system to replace the spring-loaded bellows in the ST7 design. This is a low-risk design that is commonplace in the propulsion systems.

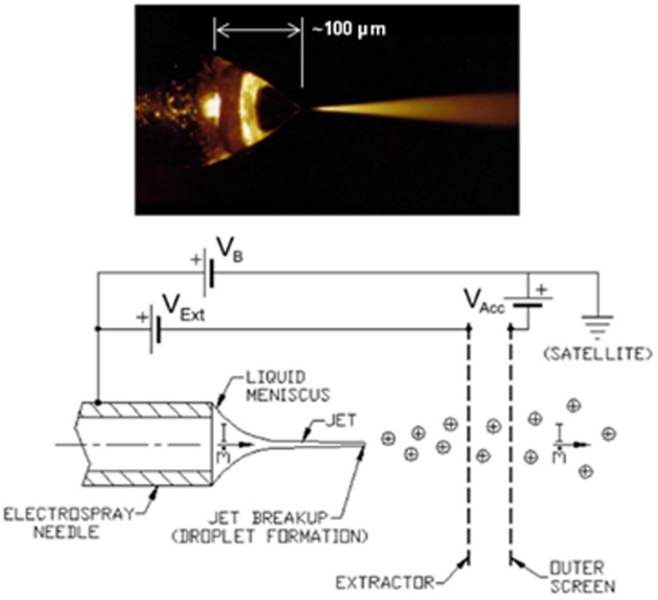


Figure 7. *A colloidal microthruster nozzle showing charged droplets and ions electrostatically accelerated to produce thrust with better than 0.1 μN precision is shown.*

Extending the demonstrated lifetime from the ≥ 2,160 hours for ST7 to the ≥ 44,000 hours required for gravitational wave mission (formerly LISA) is a major undertaking. Most of the effort since completing the ST7 flight units has gone into generating and validating a detailed model with a quantitative understanding of the "physics of failure." At this point, plume models developed in collaboration with Professor Manuel Gamero-Castaño of University of California, Irvine, have successfully predicted the accumulation of propellant on the thruster parts, which is the dominant life-limiting mechanism. Propellant accumulation allows the buildup of low-impedance paths that tend to short out the electrostatic potential that accelerates the charged droplets.

Progress: In addition to models of the propellant accumulation, there is a model for the formation of bubbles in the propellant delivery system, which is a very small diameter capillary tube that can clog easily, and a model for propellant flow in and around the electrodes that includes the plume spray, backflow from the spray, and overspray.

The models are nearly complete. Work during the past year has added temperature dependence of the charge to mass ratio to the model, further improving the models' accuracy.

The models have been validated through accelerated testing. The known failure mechanisms are currently expected to be compatible with the five-year lifetime gravitational wave mission (formerly LISA) requirement.

A piezo-actuated microvalve to control propellant flow is under development by Busek through a Phase II SBIR contract. The valves are tricky to build and qualify for space. Busek has a third-generation design that is currently undergoing life testing and appears to meet performance requirements for ST7.

The demonstrated performance levels of the ST7 flight units are summarized in Table 5, which shows the key milestones to complement the development plan shown in Figure 6 as well as some of the performance metrics that have been achieved.

Planned Activities

A critical technology for NASA are CMNTs. Lower-cost gravitational wave missions are likely to have two years of science operations, rather than the five years of the gravitational wave

Milestone	Date
Complete 3,400-hour life test of ST7 EM colloid thruster system	Nov 2006, Completed
Complete 3,000-hour wear test of 6 independent LISA breadboard colloid thruster systems to identify failure mechanisms	Sept 2007, Completed
Demonstrate Micronewton Thruster Performance	Nov 2007, Completed
Delivery of Flight-Qualified ST7 CMNT Clusters	May 2008, Completed
Integration of ST7 CMNT clusters onto the LISA Pathfinder spacecraft	Nov 2009, Completed
Complete accelerated testing of ST7 CMNT thruster design	Nov 2010, Completed
Delivery of Flight-Qualified LISA Pathfinder FEEP Flight Units	October 2012
Complete CMNT LISA prototype (PM) microthruster design	April 2011
Complete FEEP LISA prototype (PM) microthruster design	End 2012
Begin long-duration wear test of both CMNT and FEEP LISA prototype microthrusters	October 2011
Complete performance measurements of LISA PM microthrusters	April 2012
Milestone for 8,000 hours of PM wear test	December 2012
Milestone for 20,000 hours of PM wear test	PDR
Milestone for 40,000 hours (plus margin) of PM wear test	CDR

Table 5. *The Nominal Microthruster Subsystem Requirements summary for the LISA baseline concept (per a peer review dated December 18, 2009), LISA Pathfinder and preliminary requirements for NGO are shown, as well as the demonstrated performance levels for ST7.*

(formerly LISA) baseline concept, and lifetime testing of the CMNTs should be re-planned accordingly.

Proposed activities for FY12 are:

1) Perform an accelerated test of the microvalve currently under development by Busek. This would involve purchasing a microvalve from Busek; performing baseline functional tests, cycling tests, and total propellant throughput test (1 liter) (For FY13: Conduct materials and soft goods investigations looking at long-term propellant compatibility with microvalve materials and adhesives.)

2) Demonstrate extended thruster performance. From the FY11 closeout activities, three approaches will be defined to extend thrust range: software only, small hardware changes (to electrodes only), and significant hardware changes (e.g., flow system and electronics). This task will test both the software and electrode modification approaches with direct thrust measurements

3) Demonstrate improved thruster response time. Through software changes only, show an improved thrust response time; design any hardware changes that would be necessary to improve response time if software changes are not sufficient.

2.1.2 Phase Measurement System (PMS) Technology

Summary

Phasemeter technology development during FY11 focused on four main efforts: 1) incorporation of optical communication capability in the phasemeter; 2) construction and testing of an FPGA-based digital signal processing core board as part of a development effort for the core; 3) revision, layout, and testing of an analog front-end design, and; 4) laser frequency stabilization activities including arm-locking simulations, implementation of a LISA-Pathfinder-style Mach-Zehnder frequency reference, and implementation of a Pound-Drever-Hall cavity frequency reference.

The Phase Measurement System (PMS) was evaluated in 2007 by the Beyond Einstein review panel of the National Research Council [PMS-1]. Early in 2010, testing in the interferometry test bed [PMS-2] validated the operation of the key components of the PMS in a laboratory environment.

Technology Description

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 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 8a 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 an RF frequency between 1 and 20 MHz. A prototype of the front-end electronics is shown in Figure 8b, along with the measured performance of both the noise and the phase response over the RF measurement band. The measured performance exceeds the requirements.

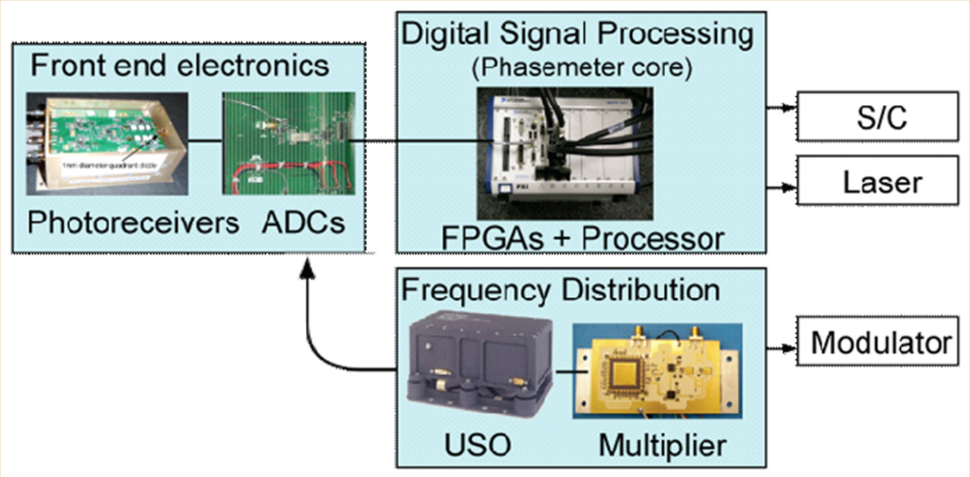


Figure 8a*. A block diagram of the phasemeter and phase measurement subsystem is shown.*

Figure 8b. *his image shows a quadrant photoreceiver that meets the requirements for noise and phase flatness over the LISA signal bandwidth, which comes from the varying Doppler shift resulting from relative motion between pairs of spacecraft. Alternate concepts are typically enveloped by LISA's requirements of 2–20 MHz.*

The digital signal processing core (see Figure 9) phase-locks an electronic oscillator to the phase of the beat note and provides an estimate of the phase to the spacecraft for processing and to the local laser for phase-locking to the incoming laser. Phase differences among the quadrants of the photodetector allow the spacecraft to sense the incoming angle of the beam received from the far spacecraft in both pitch and yaw. The drag-free and attitude control system (DFACS) uses this information to track the beam and keep the telescope pointed in the correct direction. The combined signals from all four quadrants are used to generate an estimate of the distance between the spacecraft.

Parameter	**LISA Baseline Requirement**	**Demonstrated performance**	**Units**	**Estimated NGO**
Phase sensitivity	< 2	< 1	μcycles/√Hz	same
Dynamic range @ 3 mHz	> 2 x 108	> 2 x 1012	none	Same
Frequency range	2-20	0.2-20	MHz	1-10 MHz
Phase-locking error	<10-2	<10-5	cycles/√Hz	same
Frequency slew rate		758	kHz/s	
Amplitude sensitivity		<0.014	μcycle/%	

Table 6. *NASA's phasemeter meets all critical performance requirements for the LISA baseline concept as well as all of the phasemeter auxiliary functions defined above. The requirements for an ESA-led NGO and NASA-led mission are expected to be similar because the concepts to date rely on interspacecraft laser interferometry.*

The PMS also includes an ultra-stable oscillator (USO) as a digital clock signal and a clock noise distribution and extraction system that allows the removal of clock noise in post processing by multiplexing the noise onto RF carriers above and below the main beat note for the laser in each arm. No additional development work on this part of the system was pursued in FY11.

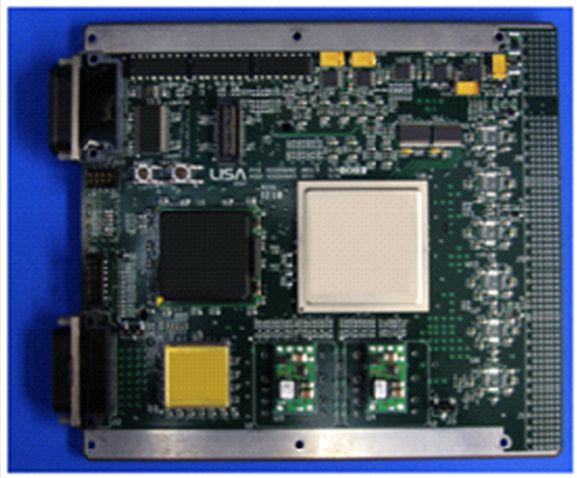


Figure 9. *The phasemeter signal processing core is shown.*

The critical phasemeter performance requirements for the gravitational wave (formerly LISA) baseline concept are shown in Table 6, along with the laboratory-demonstrated values. The demonstrated performance exceeds the requirements in all cases, sometimes with a considerable margin. At this early stage, it is desirable to have a performance margin to allow for rebalancing of the error budget and noise allocations. Table 6 also shows the requirements for the ESA-led NGO mission, as they are currently understood. The requirements for the NASA-led Space-based Gravitational-wave Observatory (SGO) mission have not yet been defined.

Status, Progress, and Plan

Status of development: The JPL phasemeter development team has made progress on the photoreceiver, analog front-end, digital processing, and controller. The JPL team is preparing for testing of the core signal processing board. In addition, a substantial testbed has been built up that has, among other things, been used to demonstrate the essential end-to-end gravitational wave measurement. A fairly high level of realism has been achieved, and it was published in a high-visibility journal in early 2010, which has generated some interest and press outside the community [PMS-2].

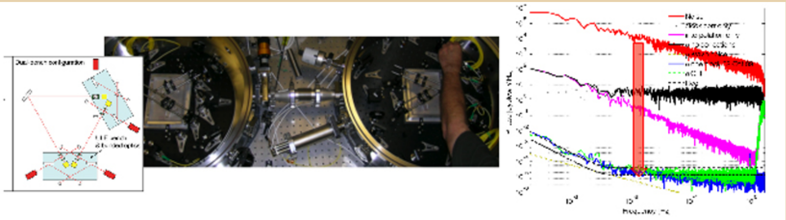


Figure 10. *Left: A top view of the LISA phasemeter testbed is shown. Center: A photograph of the LISA phasemeter testbed is shown. Right: The measured results meet requirements. NASA's phase measurement system was demonstrated to be at TRL 4 in a performance test (results at right) in an interferometer-system-benchtop testbed. NASA's strategic investment has led to a phasemeter and testbed capability unrivaled elsewhere.*

Progress: Work continues on the signal processing core board of the phasemeter to finish the firmware, perform testing, and develop a system controller board and software. All-digital testing (no analog front end) allows rapid testing of key aspects of the firmware and system operation without requiring optics and lasers.

A photoreceiver has been constructed with a commercial photodetector and preamplifiers and meets noise and phase stability requirements. The following stage that further amplifies, filters, and digitizes the analog signal from each of the four quadrants and allows for injection of a calibration tone for removing jitter in the digital sampling clock has been designed and built during FY11 to complete the prototype front end.

Milestone	Date
European complete Phase Measurement Subsystem (TRL 5/6 ?)	Mid 2012
European complete Phase Measurement Subsystem in full optical configuration	Mid 2013
NASA Phasemeter breadboard (TRL 4)	Completed Nov. 2007
NASA Photoreceiver (TRL 4)	Completed Nov. 2007
NASA Phasemeter (digital unit) TRL 5 Report	Completed Jan. 2009
NASA TDI demonstration with laser comm. (Interferometer Gate 1)	Mar. 2011
NASA Photoreceiver TRL 5	Completed, Nov. 2009
NASA Phase measurement system (TRL 6)	Dec. 2012

Table 7. *Technology Development Milestones*

Finally, an optical bench with a Mach-Zehnder interferometer has been added to the interferometry test bed. This is the same type of frequency reference used on the LISA Pathfinder mission. If this testing is successful, it could lead to a simplification of the laser frequency stabilization system for NGO or SGO. Figure 10 shows a photograph of the testbed as viewed from the top. The testbed represents two of the three spacecraft of the complete observatory (left-hand side of Figure 10). Figure 10 (right-hand side) also shows preliminary results that indicate that the performance of the system meets the requirements at frequencies above approximately 0.1 Hz.

Plan: Table 7 shows the key milestones from the program as it has been up until now. The performance milestones, as indicated in Table 6, have already been met, and development efforts have focused on demonstrating the performance with increasing fidelity in the environment, as is appropriate for increasing technology readiness. SGO and NGO will likely have comparable requirements to LISA because all of the concepts rely on laser interferometry between distributed spacecraft, and this sets the basic performance and functional requirements for the PMS. The one exception is a proposed atom-interferometer-based measurement that targets different science. NASA's investment in the PMS has left the U.S. with a strategic asset that supports an ESA L-class mission contribution as well as a U.S.-led mission. No other effort has similar design maturity, capability, or performance.

Planned Activities

The primary objectives of FY12 activities are to:

- Demonstrate the viability of the phasemeter under different credible mission scenarios in which the requirements differ from LISA.
- Maintain NASA as a viable partner in the (likely) scenario that ESA and NASA will partner in some form (ESA L-class or NASA-led).
- Demonstrate the viability of techniques that can simplify a gravitational wave mission (e.g., relax requirements on laser power, telescope diameter, orbital dynamics, and flight system complexity).

The proposed activities for FY12 are:

1) Design and demonstrate modifications to the phasemeter that support the relaxation of the LISA baseline concept requirements on laser noise, orbital parameters, and received optical power.
2) Laser Frequency Control: Complete hardware armlocking simulation and demonstrate the design performance of Mach-Zehnder stabilization.
3) Assemble and test an analog signal chain pre-amp board.

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2.1.3 Telescope Spacer Technology

Summary

The telescope design for the LISA baseline mission may be adequately satisfied by a classical Cassegrain-style optical system—either on-axis or off-axis. By itself, therefore, it is not a particularly risky development item. However, the gravitational wave application is for a precision length measurement system, not an imaging system, and so some of the requirements are different from those for an imaging system. 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. Most typical imaging applications for a telescope do not have these requirements.

A specific risk reduction activity has been to develop and test a candidate structure to keep the primary-to-secondary mirror spacing dimensionally stable under realistic environmental conditions, allowing retirement of that risk without the cost of making a real (and expensive) optical telescope.

Figure 11 shows a photograph of a four-legged "quadpod" silicon-carbide-based telescope spacer structure. Testing has shown that the prototype structure can meet the dimensional performance requirements at the expected operating temperature of -65°C.

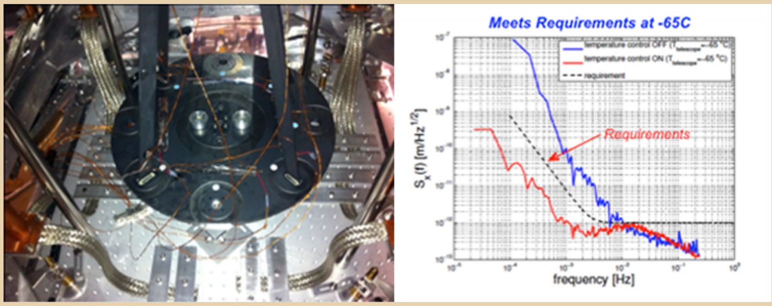

Figure 11. Left: *A primary mounting plate of a silicon-carbide telescope spacer structure is shown inside a thermal test chamber. The purpose of the white tissue paper is to protect the polished mirror mounting pads.* ***Right:*** *Results showing that the spacer meets dimensional stability requirements at the predicted operating temperature for the telescope.*

Technology Description

The LISA concept telescope, although based on a conventional optical design, is optimized for precision pathlength measurements, so it must be dimensionally stable at the 10^{-12} m/√Hz level under the operating conditions expected for the LISA concept spacecraft, which include low temperatures (-70°C) and temperature gradients, both axial and transverse. Excellent knowledge of the physical properties, particularly the CTE, is also required to maintain alignment tolerances to better than 1 micron. Table 6 shows the nominal performance requirements for the LISA baseline concept, NGO, and projected SGO missions.

Figure 12 shows a photograph of the prototype silicon-carbide-based spacer in a four-legged, or "quadpod," design. The material, silicon carbide, was chosen because its very high thermal conductivity would tend to minimize the large expected thermal gradients. An axial gradient is expected because the secondary mirror views cold space and the primary mirror backs up against the optical bench, which must be near room temperature

Parameter	Derived From	Classic LISA Baseline	NGO	SGO
Net Wavefront quality of beam exiting telescope	Pointing	$\lambda/30$	$\lambda/30$	$\lambda/30$?
Typical wavefront error of reflection surfaces	Pointing	$\lambda/100$ per surface	$\lambda/100$ per surface	$\lambda/100$ per surface ?
Typical wavefront error transmissive surfaces	Pointing	$\lambda/130$ per surface	$\lambda/130$ per surface	$\lambda/130$ per surface ?
Telescope subsystem pathlength stability	Pathlength Noise/Pointing	$2\,\mathrm{pm}/\sqrt{\mathrm{Hz}}\cdot(1+(1\,\mathrm{mHz}/f)^4)^{1/2}$ over LISA mbw	$2\,\mathrm{pm}/\sqrt{\mathrm{Hz}}\cdot(1+(1\,\mathrm{mHz}/f)^4)^{1/2}$ over LISA mbw	?
Field-of-View (Acquisition)	Acquisition	+/- 155 μrad	+/- 155 μrad	?
Field-of-View (Science)	Orbits	+/- 10 μrad	+/- 10 μrad (TBC)	?
Transmitted beam diameter on primary mirror	Shot noise/ Pointing	0.92·D	0.92·D	?
Primary Mirror Diameter	Noise/ pointing	400 mm	400 mm (TBC)	250 mm (?)
Beam size on bench	GRS	5 mm	5 mm	5 mm ?)
Entrance Pupil	Pointing	Entrance of beam tube (or could be located at primary)	Entrance of beam tube (or could be located at primary)	?
Location of image of primary mirror (exit pupil)	Pointing	~10 cm (on axis) behind primary mirror	~10 cm (on axis) behind primary mirror	?

Table 8. *The nominal telescope requirements for space-based optical interferometric gravitational wave missions are shown.*

to take advantage of the near-zero coefficient of thermal expansion (CTE) of Zerodur. A transverse thermal gradient is expected because the top deck of the spacecraft has solar cells pointed toward the sun and the bottom deck is facing cold space. In addition, the distribution of avionics on the spacecraft tends to be anisotropic. A tripod spacer design is preferred for mechanical stability, but four legs were chosen to match the symmetry of the main science detector, which is a quadrant photodiode. The shadow (and diffraction pattern) cast by the legs would fall equally on each quadrant such that, for a well-aligned system, any small motion of the spacer (such as a rotation) would, at least in principle, affect each quadrant equally. A more symmetric design for a spacer is a simple cylinder, but early on in the design process we could not get a vendor to agree to make the walls of the cylinder thin enough to meet our mass target. If a different material were to be tried, the cylindrical design would definitely be revisited.

Figure 12. *A silicon-carbide telescope spacer is shown with white paper to protect the polished mirror mounting pads.*

An on-axis Cassegrain with a silicon-carbide (SiC) spacer is fairly conventional, but stray light control will be a challenge. The SiC spacer should be achievable; lab demonstrations to date have had technical difficulties, and novel solutions involving antiscattering masks and nanotube absorbers seem promising. However, realistic measurements are needed to provide support for the studies.

Figure 13 shows the results of a thermal model that verifies that the high thermal conductivity of silicon carbide minimizes the thermal gradients under the expected on-orbit environmental conditions. ESA is pursuing a different material for the spacer design. Carbon Fiber Reinforced Polymer (CFRP) composite materials have the advantage that the CTE may be tailored by controlling the composition and layup of the composite, but CFRPs have the disadvantage that the material absorbs water and changes dimensions. Preliminary testing at the University of Florida has shown that at least one candidate design does not meet requirements. This does not necessarily mean that there is no CFRP design that will work but, rather, that additional care is needed in design and testing and that it is advisable to attempt another demonstration.

Status, Progress, and Plan

State of development: Figure 14 shows a diagram side view of the telescope spacer in a thermal test chamber at the University of Florida. The test chamber is large enough to test a 600 mm high × 400 mm wide structure at low temperatures, and the chamber has been instrumented with an optical system and the ability to apply thermal gradients. The idea is to construct an interferometer on axis with small mirrors and to lock a laser to the cavity and compare it with a reference cavity. The results shown in Figure 11 confirm that the spacer design meets requirements.

Along the way, the basic mechanical properties of the silicon-carbide material, such as the CTE, have been measured and found to be in good agreement with the vendor's data. The main remaining work is to check for tilts in the structure as it is heated and cooled and as a gradient is applied. Tilts are particularly harmful because there is currently no provision in the proposed telescope design to correct for an off-axis misalignment. Full correction would require a five degree-of-freedom mechanism, which is extremely expensive as well as complicated. The telescope is 4lanned to have a focus mechanism, but this is a single degree of freedom actuator and corrects only on-axis misalignments.

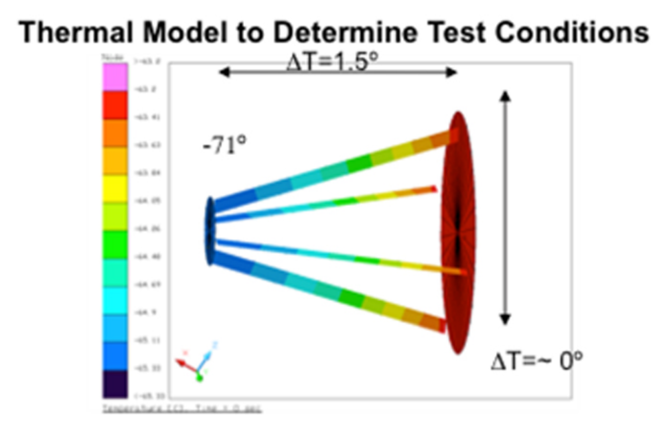

Figure 13. *The results of a thermal model that verifies that the high thermal conductivity of silicon carbide minimizes the thermal gradients are shown.*

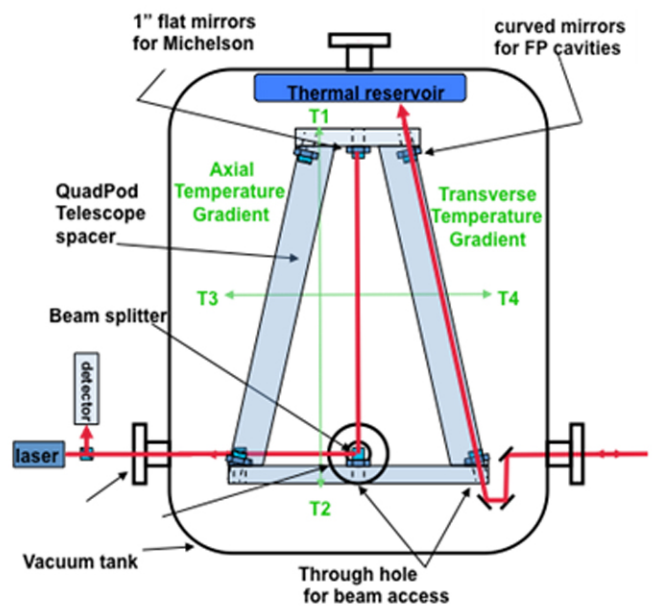

Figure 14. *The telescope spacer test setup at the University of Florida, showing on- and off-axis interferometers, is pictured.*

Planned Activities

The proposed activities are to focus on areas where the requirements for LISA, NGO, and SGO differ from standard optical design practices. The baseline concept for the gravitational wave (formerly LISA) telescope is not settled. The two competing designs promise different benefits, but development and, more importantly, lab demonstrations are only just beginning. The major technical challenges in the gravitational wave telescope are stray light control and optical pathlength stability stemming from the stability of the primary-secondary spacer. Note that two telescopes are needed per arm, so a three-arm mission requires six telescopes for flight, as well as spares and units for ground testing. This means that these units must be designed for small-scale manufacturing, so there is a premium on simplicity and low cost for design, construction, and testing. The specific proposed activities are as follows:

1) Complete a requirements study to develop straw-man NGO specifications and kick off a study with an aerospace industrial partner to validate the design, including a detailed tolerance analysis and an assessment of manufacturability. For FY13, this work would continue on to procure a first prototype optical design that could be used for testing.

2) Continue studying scattered light reduction techniques by updating an existing LISA baseline model for NGO requirements and finish a promising anti-scattering mask design. In parallel, begin to make measurements on representative substrates to test different techniques for reducing scattered light, including a strategically placed and shaped hole, anti-reflection coatings, and blackening coatings made with carbon nanotubes with a proprietary process invented at Goddard.

2.1.4 Laser Component Technology

Summary

The laser subsystem work has been focused on identifying alternative components for the master oscillator laser and studying the reliability of critical components for the optical power amplifier. Current work has focused on studying the noise properties of candidate master oscillator lasers and the environmental sensitivity of the coupler that combines pump laser light and the optical signal for a cladding pumped amplifier.

Technology Description

The basic architecture for the laser system is shown in Figure 15. The basic idea is to combine subsystems that are separately optimized for specific functions into an integrated subsystem that satisfies requirements. The master oscillator laser is chosen for very low frequency and amplitude noise. The output power is typically 25–100 mW at an optical wavelength of 1064 nm and passes through a phase modulator that is used to encode the clock noise, commands, and data onto the main science beam for transmission between the spacecraft. The output of the modulator, typically 10–15 mW, is then introduced into an optical power amplifier that generates the full power required to make the measurement. The baseline master oscillator component has been a diode-pumped solid-state laser known as a non-planar ring oscillator, or NPRO, for about 30 years. These lasers were originally chosen because they had the lowest known free-running frequency noise with reasonable output power levels.

Figure 15. *Pictured is the baseline laser system architecture: master oscillator laser, modulator, optical power amplifier.*

The modulator is typically lithium niobate (LiNbO3) although, more recently, potassium titanyl phosphate (KTP) has been demonstrated as well.

The baseline optical power amplifier is cladding pumped, which uses broad-area pump lasers at about 980 nm to pump a multimode fiber that contains a Yb-doped single-mode fiber that propagates the signal. Single polarization operation is required because the distance measurement is performed using interferometry. Lasers will only form interference fringes with light of the same polarization state.

Nominal requirements for the LISA baseline concept laser system are:

- 2 W output power
- 1064 nm wavelength
- 100 Hz/Hz frequency noise at 1 mHz
- RIN < 10^{-4} at 1 mHz
- 5-year mission lifetime

Progress, Status, and Plan

Because of the concerns in Europe regarding the only vendor providing a space-qualified NPRO laser, the GSFC laboratory work has principally investigated alternate laser technologies for the master oscillator element. Noise evaluations of several technologies have been completed, pointing to the external cavity laser as the most promising alternative to the NPRO, as it is shot noise limited above 1 MHz, and its frequency noise is closest to the NPRO compared to the other technologies. Figure 16 shows an external cavity laser (ECL); the compactness and low mass of the ECL relative to the NPRO is apparent.

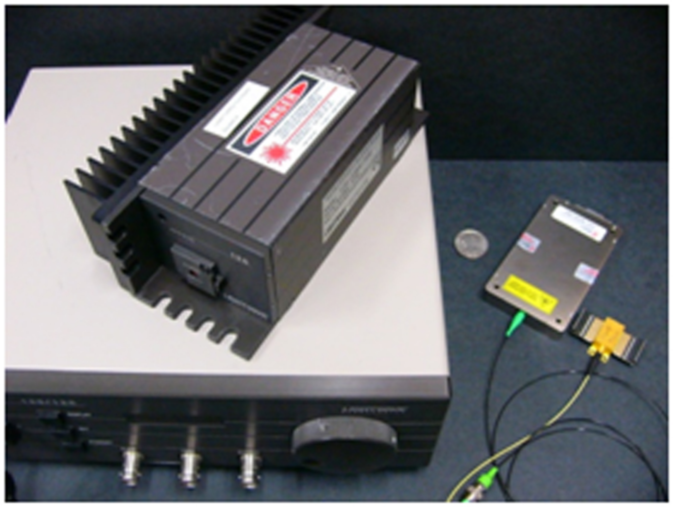

Figure 16. Right: *Alternate master oscillator candidates are shown.* ***Left:*** *Existing baseline master oscillators are shown.*

Lucent Government Systems (LGS) has focused on the reliability of a cladding-pumped fiber amplifier. LGS has assessed the reliability of its preferred concept, tested some components, and built a breadboard. Considerable work remains to be done to get to flight readiness with a complete laser subsystem, including a master oscillator, modulator, power amplifier, and redundancy components. Figure 17 shows a prototype amplifier.

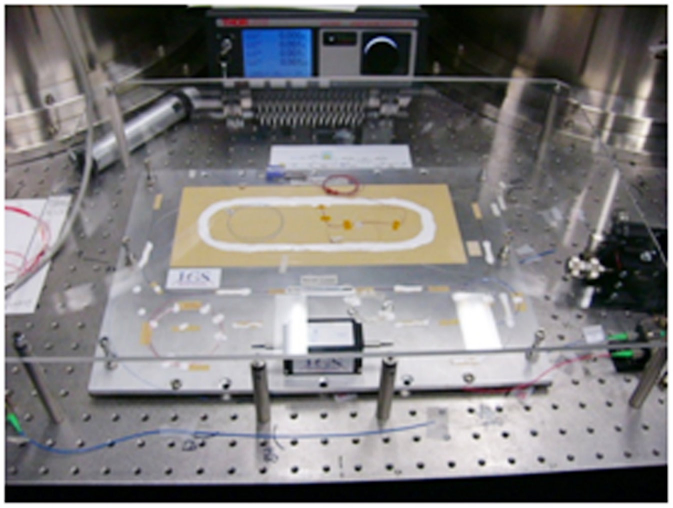

Figure 17. *An optical power amplifier constructed by Lucent Government Systems (LGS) is shown.*

Figure 18 shows some of the radiation testing done on one component for the optical amplifier, an optical coupler. The small effect on the coupler is consistent with the localization of degradation to the component pigtails. Radiation effects on most of the amplifier have been designated as low risks by LGS. A detailed study of radiation effects on the amplifier gain will be undertaken in FY12.

Figure 19 shows the results of some of the noise measurements made on different candidate master oscillator lasers. The ECL laser operates at a wavelength in the commercial telecom band near 1550 nm; the company's models predict similar noise performance with a redesign to allow lasing at 1064 nm.

Next Steps: The NGO mission team—including Karsten Danzmann, NGO mission scientist; Paul McNamara, LISA Pathfinder project scientist; and Dennis Weise, Astrium Interferometry lead—has specified that the NGO laser baseline architecture is very close to the LISA design, employing a low-noise oscillator followed by a ~2 W power amplifier at 1064 nm. They have also enthusiastically supported the development of this technology in the U.S. as a candidate U.S. contribution to NGO. The 2 W 1064 nm MOPA design offers the highest possible sensitivity, the crucial factor in gravitational wave astronomy, and also allows margin for power tradeoff with telescope size, etc. At the current specified output power of 2 W at the beginning of life, a cladding-pumped power amplifier may be the only viable way to get the required level of redundancy in a design for spaceflight. Testing done in FY11 has indicated that the LGS amplifier performance at 2 W is within a factor of ten of NGO requirements for the differential phase noise and amplitude noise, with temperature fluctuation limiting the noise performance. In FY12, the amplifier will be temperature stabilized, allowing a demonstration of the full NGO requirements.

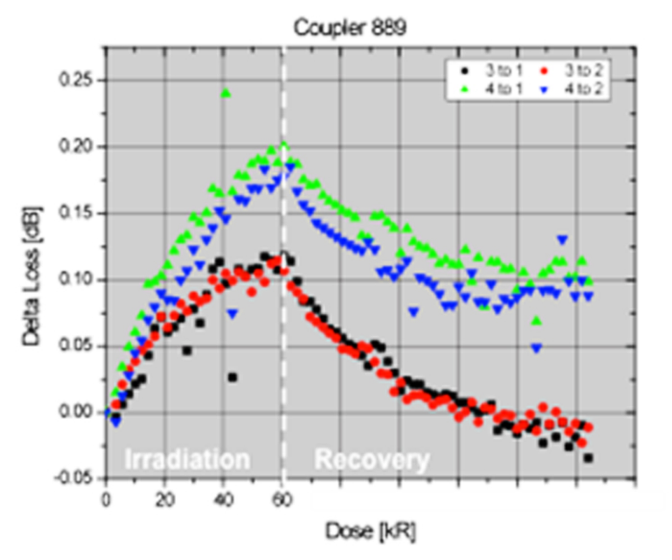

Figure 18. *A gamma-irradiated fiber coupler is shown. The small observed effect is consistent with degradation to the component fiber pigtails.*

Planned Activities

Proposed activities for FY12, pending selection:

1) Develop an external cavity laser at 1064 nm. A proposed SBIR Phase 2 contract, if funded, will take an existing design at 1550 nm and migrate it to 1064 nm. Follow-on work in FY13 and FY14 will include further reliability testing and accelerated chip aging. The goal is to have a master oscillator laser by October 2012.

2) Perform a system-level noise test of the complete MOPA laser subsystem, including a frequency stabilized NPRO seed and temperature stabilization of the LGS amplifier, demonstrating that it meets the requirements for the LISA baseline concept system for frequency noise and amplitude noise simultaneously. The NPRO will be replaced by the 1,064 nm ECL when it becomes available.

3) Continue laser reliability studies of high-risk components for a cladding-pumped amplifier at Lucent Government Systems (LGS), including a detailed study of the irradiation of the gain fiber. The goal is to have an amplifier that can meet specifications by October 2012.

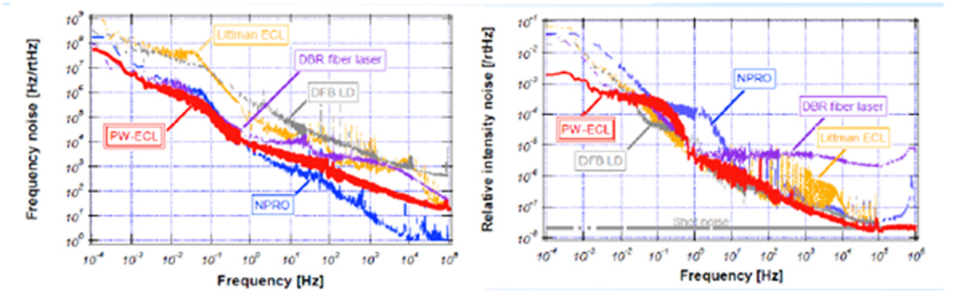

Figure 19. Left: *The frequency noise of various candidate master oscillator lasers is shown.* ***Right:*** *The relative intensity noise (RIN) of various candidate master oscillator lasers is shown.*

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2.1.5 Laser System Architecture Technology

Summary

The reliability of a system can be better than the reliability of some of the components. We have begun a system-level study to understand how the architecture of a system can affect the reliability and chose the laser subsystem as a starting point. The intention is to extend the study at a later point to the entire mission. The standard reliability model is to use redundancy—that is, a copy, or multiple copies, of a system and to switch between them if one fails. Part of the motivation to start with the laser subsystem is to see if it is possible to take advantage of the fact that some components are more reliable than others and to come up with a design that improves the system reliability without duplicating everything. Current work has been focused on the development of a reliability block diagram and construction of a tool for calculating the reliability as a function of time for the various architectures. Using estimates for the reliability of currently available components, we can make a quantitative comparison between different designs. We can also run the problem in reverse and derive requirements for the components based on the design.

Technology Description

It is important to keep in mind that the architecture and reliability study is conceptually quite different from the focus on component-level reliability in the laser subsystem development work described in an earlier section of this report. As part of that development effort, the components are examined to identify key aspects of the design that may limit the reliability. Often, these aspects are packaging or materials related. Then testing is performed to try to improve these aspects. For the architecture study, the emphasis is on how components are interconnected, not on the components themselves.

Figure 20 shows several different examples of possible systems architectures. The top configuration shows two separate laser systems driving two separate telescopes. This has no redundancy at all, but represents the minimum number of components required to make the measurement and serves as a reference architecture. The middle configuration shows the traditional architecture widely used for redundancy with two copies of each laser subsystem driving a single telescope through a selector switch. This is the baseline configuration for the laser subsystem and shows a two-deep level of redundancy for either telescope. Any successful architecture would improve on the reliability of this configuration. The bottom configuration shows components cross-strapped between different subsystems. The idea is that any master laser could be used to drive the modulator and optical power amplifier of either telescope. This represents a four-level deep redundancy. Because some components may be more reliable than others, it may be possible to eliminate components as well as improve the redundancy by increasing the number of backup devices available by using appropriate cross-strapping.

Technical relevance: Laser system reliability is primarily a function of the packaging of the components, not the inherent reliability of the devices. Commercial terrestrial telecom investment has driven the reliability of components at 1550 nm to extremely high levels while maintaining low cost, but the operating wavelength for LISA has historically been 1064 nm (Nd:YAG) and components are not as well characterized or as readily available at that wavelength. Furthermore, the materials issues for component construction are also different, meaning that some development is required because the results and methods for 1550 nm may not apply.

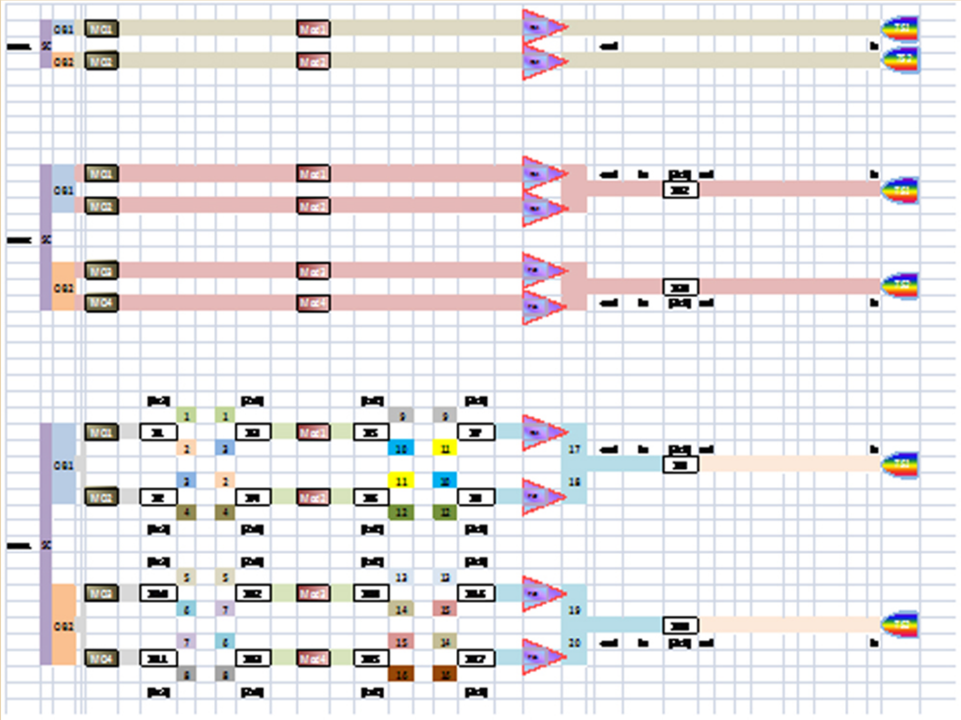

Figure 20. *Block diagrams of some of the candidate system architectures that are being considered for laser reliability studies. The top configuration is a single-string reference configuration showing two laser systems for a spacecraft. The middle configuration shows the baseline traditional completely redundant A and B string architecture. The bottom configuration shows a configuration with partial component cross-strapping.*

Progress, Status, and Plan

Work over the past year has focused on developing reliability block diagrams for the various configurations, plus a tool for calculating the reliability as a function of time for the configurations. Some component reliability data has also been collected, although it has been hard to find. Preliminary calculations suggest that the traditional architecture cannot meet the mission requirements using currently available components. Working backward suggests that the component reliability is possible to achieve, although higher than routinely available commercially. The reliability calculator needs to be tested thoroughly for all configurations before the results are ready to be used.

2.1.6 Optical Assembly Tracking Mechanism Technology

Summary

Testing of an off-the-shelf commercial inchworm actuator with flight heritage meets the requirements for the component. Figure 21 shows a photograph of the test bed constructed to test the component. The graph at the right shows that the position accuracy of the actuator meets both the nominal system requirements as well as a more stringent suballocation requirement.

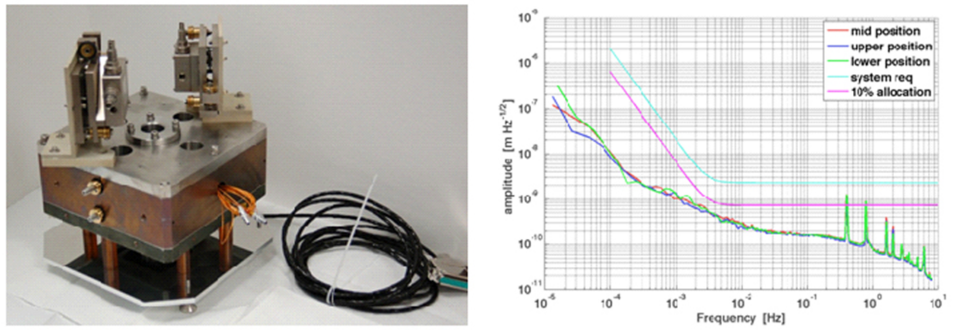

Figure 21. Left: *An OATM actuator test bed is shown.* ***Right:*** *The results herein show that the actuator meets both the total-system requirements (cyan curve) and the nominal allocation (magenta curve) requirements.*

Technology Description

The LISA concept spacecrafts are in constant motion throughout the orbit, and the line of sight between the spacecraft changes more than can be accommodated with the nominal field of view of the telescopes.

Therefore, the telescope and optical bench, which comprise the optical assembly for each arm, must be made to track the line-of-sight variations. This requires the ability to make very precise angular motions (~nrad) over a large dynamic range of angles (± 0.75 degrees). An ideal actuator for this purpose (and one with flight heritage) is an inchworm mechanism, as shown in Figure 22. The shaded horizontal piece is grasped by two piezo-electric materials—one in shear and one in compression. Coordinated motion of both piezos moves the center piece by small amounts while retaining the overall sub-nanometer accuracy and large range of travel.

Progress, Status, and Plan

State of development: The OATM work has finished the first phase. A flight-qualified actuator has been shown to have the range, resolution, and stability needed to meet flowed-down requirements. The next stage is to make a detailed design of the pointing subsystem (e.g., hinges, actuators, launch locks, and moving structure). Then a mechanical model should be tested with representative operational parts and inertial properties to demonstrate the requirements at the subsystem level.

If an optical assembly needs to be pointed in any mission concept, then a tracking subsystem will be needed. All of the orbital solutions investigated in the search for lower-cost mission concepts require telescope pointing. Bender has suggested two novel ideas that might eliminate the need to point telescopes: "transverse thrusting" and "episodic repositioning." However, the viability of these ideas needs to be studied because there are consequences for the GRS, the microthrusters, and the drag-free control system. Another technique, called "in-field guiding", substitutes a small moveable mirror as part of the telescope optics for motion of the entire optical assembly. The technical requirements for the mirror design are challenging because angular motion without an accompanying piston motion are required and, until the requirements are better known, it is difficult to assess the feasibility of such a design. Similar mirrors are under development for applications such as the point-ahead mirror, but these have very small required angular ranges and, therefore, may not be directly relevant. A detailed technical report has been prepared [OATM-1].

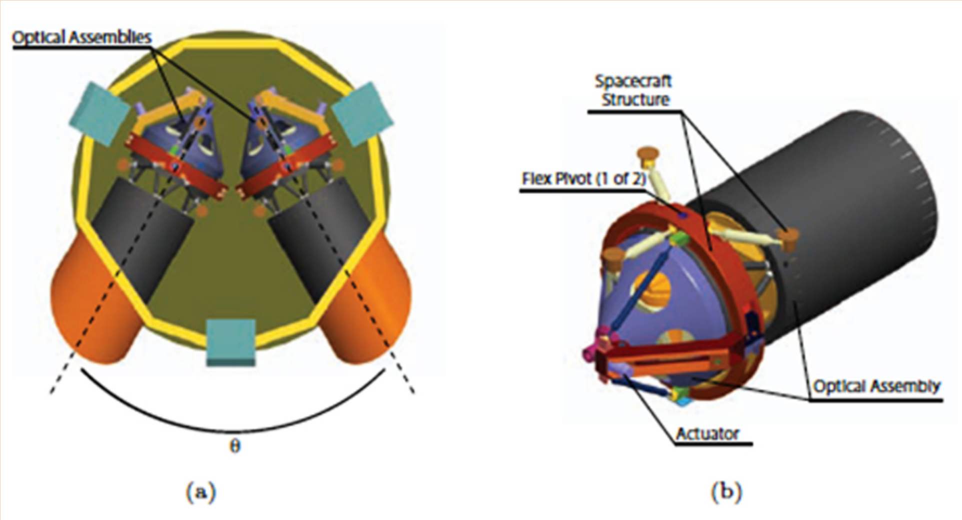

Figure 22. Left: *The top view of the LISA concept spacecraft, showing the two optical assemblies (OA) and the angle θ between the lines of site to the other spacecraft, is pictured.* ***Right:*** *A single OA, showing the flex pivot mount and the attachment point of the actuator that moves the OA, is pictured.*

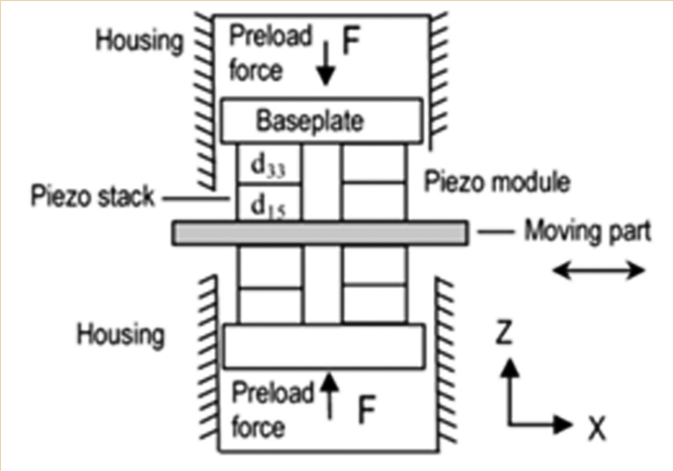

Figure 23. *A diagram of an inchworm mechanism is shown. (From the PI Website: http://www.physikinstrumente.com/en/pdf/N214_Datasheet.pdf)*

2.1.7 Custom Photoreceiver Technology

Summary

A custom-designed photoreceiver with a large area, very low capacitance per unit area, and a small dead zone between quadrants has been developed through the Small Business Innovative Research (SBIR) program. Currently in Phase 2, the program has demonstated component-level performance in excess of the specifications and is currently working on demonstrating system-level performance specifications such as quadrant crosstalk. Figure 24 shows a photograph of a prototype receiver in an industry-standard TO-5 package, with SMA connectors for each of the four channels at the bottom. The graph on the right shows the measured noise performance (the red and green curves) a factor of about two below the solid black line, which represents the nominal noise performance specification.

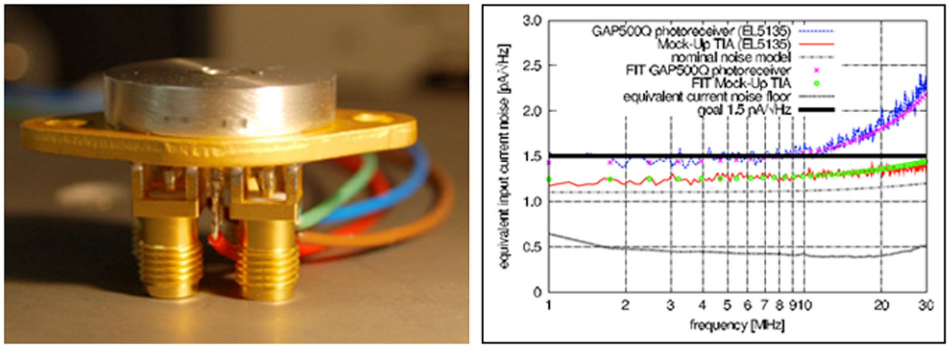

Figure 24. Left: *A custom quad receiver is shown. The package includes electronics for four channels in a TO-5 package.* ***Right:*** *Pictured are results showing that the noise performance is a factor of about two lower than the nominal requirements.*

Technology Description

The photoreceiver is composed of a 1 mm diameter quadrant photodiode plus the associated low-noise electronics. This component is the first analog component of the main science measurement chain, and in a good design the noise floor of the receiver sets the baseline sensitivity of the overall instrument. A photoreceiver that meets the nominal requirements has been developed in collaboration with the Australian National University (ANU), but a custom development effort by an industrial partner has resulted in a compact design that reduces the noise by at least a factor of two. Current work has focused on measuring component-level properties such as noise and bandwidth.

Progress, Status, and Plan

State of development: Routinely available photodetectors can be built into photoreceivers that meet LISA requirements, which are likely to be similar to any future concept. With support from the SBIR program and a grant from NASA Headquarters, this effort has produced a custom quadrant photoreceiver with very low capacitance (~2 pf/quadrant)—and, therefore, high bandwidth and low-power dissipation, low noise, and small dead-zone between quadrants (25 μm). The prototype devices have a 1 mm diameter, which is a good match to the anticipated beam sizes. Commercially available quadrant photodetetors of the same size have much higher capacitance (4–10×) and larger dead zones (100 μm). Higher capacitance means higher noise and lower bandwidth. Currently, a low-noise operational amplifer is mounted in a hybrid configuration but, ultimately, we would like to integrate transimpedance amplifiers onto the photodiode substrate to further reduce noise and stray capacitance. However, the noise and bandwidth performance of the present device has been demonstrated to exceed the tall-pole requirements. Uniformity of the photoresponse and cross-talk between the quadrants are the next requirements to be tested. The GSFC Detector Development Lab (DDL) should be able to easily flight-qualify these photoreceivers.

Technical Relevance: High-performance photoreceivers are critical to any laser interferometry in which the signal is weak. Quadrant photoreceivers, which have inherently higher capacitance and, thus, greater noise and power dissipation than single-element detectors, are needed wherever beam pointing is required. High-bandwidth, low-power dissipation, low-noise and uniform photoreceivers will almost certainly be needed by any gravitational wave detector that relies on laser interferometry. Furthermore, photodetector sensitivity can be traded off against transmitter laser power, telescope beam diameter, and arm-length, and therefore contribute system-level design flexibility.

Next Steps: Other than their modest monetary value, the photoreceivers seem like an ideal contribution to ESA and should be supported for that reason alone. This technology is not required to meet performance requirements, strictly speaking, but it provides a host of benefits and can be used in system-level trades against laser transmitter power and the telescope aperture diameter, which may have significant cost impacts. Any future laser metrology-based gravitational wave detector is likely to benefit from these improved photoreceivers.

Planned Activities

Work planned for the duration of the SBIR Phase II contract (through March 2012) is to continue testing of cross-talk levels and to perform a system-level test of the receivers in a laboratory environment at GSFC.

2.2 Euclid/WFIRST Technology

Prepared by: James Lohr (NASA/GSFC)

Summary

The National Academy of Sciences in 2010 ranked the exploration of dark energy to investigate the unexplained expansion of the universe as the top priority for science this decade. To mitigate development risk, the *Wide-Field Infrared Survey Telescope* (WFIRST, formerly the *Joint Dark Energy Mission*) Project embarked on a task to produce a functional, high-fidelity prototype of a mosaic focal plane array of near-infrared detectors that would meet or exceed all scientific requirements of the WFIRST mission.

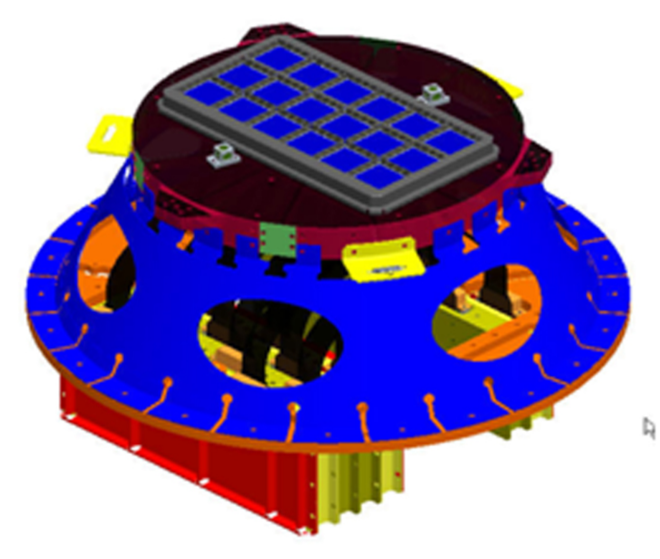

Figure 25. *The WFIRST EDU FPA is a 3x6 mosaic of infrared H2RG SCAs mounted on a circular FPA plate. A silicon carbide light shield rejects stray light from entering the detectors. Each SCA is connected from the bottom (not visible in figure) to its own SIDECAR ASIC-based sensor cold electronics (SCE) PCB via a flexible interconnection cable. The 3x6 set of SCE PCBs is mounted in several brackets, which in turn are mounted onto an SCE plate. A G10 structure (blue) is mounted on the entire detector subassembly for support.*

Although the scientific requirements continue to evolve, the detector requirements for these measurement capabilities are well enough known to define, and then fabricate and test, a useful prototype of a detector subsystem for WFIRST. Because the detector requirements are diverse, the detector performance must be characterized in detail to cover a wide range of data for the multiple scientific goals of WFIRST. These are: i) perform supernovae measurements, baryonic acoustic oscillation measurements, and weak lensing measurements to characterize the effects of dark energy; ii) perform a wide-field, near-infrared imaging and spectroscopic survey; and iii) perform an exoplanet search using the planetary microlensing technique. The current conceptual design for the mission includes one 4×7 mosaic and two 2×2 mosaics of 2k × 2k near-IR detectors, used by the imaging and spectroscopic channels, respectively.

During FY11, PCOS SR&T funding was provided to the WFIRST Project to help fund the development of a Focal Plane Assembly (FPA) Engineering Development Unit (EDU) (shown in Figure 25). This fully functional device is intended to mitigate the development risk of the largest near-infrared focal plane ever intended to fly in space.

As a result of this support, the Project will be able to demonstrate that the FPA EDU is functional by the end of FY11. Plans for additional, more detailed characterization are in place, but execution is pending funding availability in FY12. This testing is central to understanding the performance achieved and how well this design concept will satisfy the WFIRST requirements.

Technology Description

WFIRST detector requirements include: ~2.1 micron cutoff; relatively large format (e.g., 6k × 12k pixels) in order to enable a wide-field survey in the 5-year mission timeline; low readout noise (~10–12 e^- single CDS); low dark current (<0.05 e^-/sec at 100 K); plus high sensitivity (quantum efficiency), low persistence, low hot-pixel outage, flexible science mode and guide mode readout schemes, flexible reset options, and other features in order to provide maximum scientific return on all measurements within the 5-year mission timeline.

The detectors that best meet the multiple requirements of WFIRST are Teledyne's infrared (HgCdTe) H2RG sensor chip assemblies (SCAs), paired with the SIDECAR™ ASIC focal plane electronics (shown in Figure 26). This suitability was established as a part of the open competition for these devices.

The IR H2RG is a well-established, well-proven, high-performing Teledyne product for the JWST configuration. Getting from JWST to WFIRST is considered a low-risk leap; the difference in detector cutoff is expected to be transparent, and the SCA package has significant heritage from previous package designs.

The WFIRST SIDECAR™ ASIC Sensor Cold Electronics (SCE) board is designed for space flight application. It derives its heritage from Teledyne's SIDECAR™ "development" board, which is widely used in laboratory, prototype, and ground-based applications. In the flight-representative WFIRST SCE, the SIDECAR™ ASIC chip is mounted onto an aluminum nitride ceramic land-grid array (LGA) package, which provides high mechanical strength and margin to ~80 K, very low thermal resistance, and a very small footprint (a few square centimeters) over conventional focal plane electronics.

The Teledyne SIDECAR™ ASIC is a fully programmable control and digitization system for analog image sensors. The system is designed to operate at temperatures from 300 K down to low cryogenic temperatures (~34 K). The SIDECAR™ ASIC's architecture is divided into major blocks: analog bias generator; A/D converter; digital control and timing generation; data memory and processing; and digital data interface. The SIDECAR™ is designed in

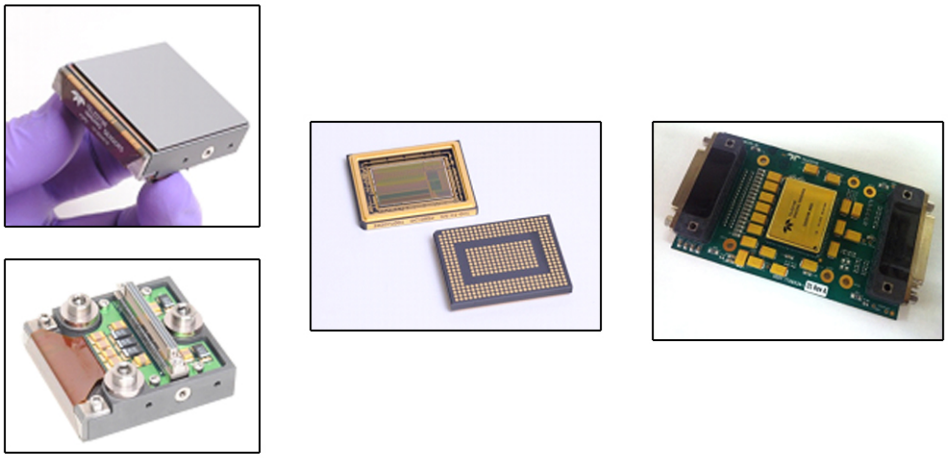

Figure 26. Left: *H2RG SCA on silicon carbide package developed for WFIRST.* ***Center:*** *SIDECAR ASIC mounted on ceramic land-grid array package developed for WFIRST.* ***Right:*** *Sensor cold electronics (SCE) board developed for WFIRST.*

0.25-micron CMOS design rules. The SIDECAR™ ASIC is also a well-established product (for room temperature operation) on the *Hubble Space Telescope*.

Each SCA/SCE pair (plus an interconnection cable between them) forms a unit cell for assembling an N×M mosaic focal plane array. WFIRST has designed and fabricated a 3×6 mosaic FPA EDU that is expected to meet all WFIRST mission requirements. The EDU FPA is a stand-alone subsystem that takes in photons, detects them, digitizes the detector response, and outputs the data through electrical interconnection to the outside world to provide a complete "photons in, bits out" assembly.

The infrared H2RG produced for the WFIRST EDU FPA used existing manufacturing recipes. No development work was performed using PCOS funding in the production of the H2RG SCAs for the EDU FPA. However, PCOS funded the purchase of twelve (12) SCA packages and temperature sensors for packaging of 12 SCAs for the EDU FPA and for obtaining additional performance data.

Twelve SCA packages were procured from GL Scientific. The SCA packages were a recurring purchase of a package design developed under other, previous funding. These SCA packages bring out the full functionality of the H2RG ROIC and can operate at temperatures from room temperature to ~20 K. The pedestal is made of silicon carbide, a lightweight material that greatly reduces the mass of a SCA compared to molybdenum-based SCA packages. Silicon carbide also is a CTE-matched material to typical materials, such as gamma-alumina, used for FPA-to-instrument interfaces.

The temperature sensors procured for use on the SCA packages are a recurring purchase of Cernox sensors with SD (silicon diode) package type from Lakeshore. These temperature sensors have excellent stability, high sensitivity over a broad temperature range (~100 mK to 420 K), and are good general sensors for use in cryogenic space applications because of their radiation hardness.

Figure 27. *A photo of a prototype of the silicon carbide light shield for the EDU FPA is shown.*

The WFIRST EDU mosaic FPA hardware design and fabrication were supported by other funding. The EDU FPA includes a thermally isolating, conical interface structure between the mosaic detectors and their corresponding SCE assemblies and provides mechanical support, protection, and a light shield for rejection of incoming stray light. The light shield is designed to fit closely on top of the 3×6 mosaic of H2RG SCAs (Figure 27). It is constrained at 12 fastener attachment locations to the mosaic plate. The light shield is fabricated in the same type of silicon carbide as was used to fabricate the SCA pedestals.

WFIRST is currently performing assembly, integration, and cold functional test of the FPA. PCOS provided the funding for the electrical and operational integration of the characterization facility for basic and detailed functional testing. Additional tasks supported by the PCOS SR&T funding are FPA integration and alignment, and basic testing of the FPA. As

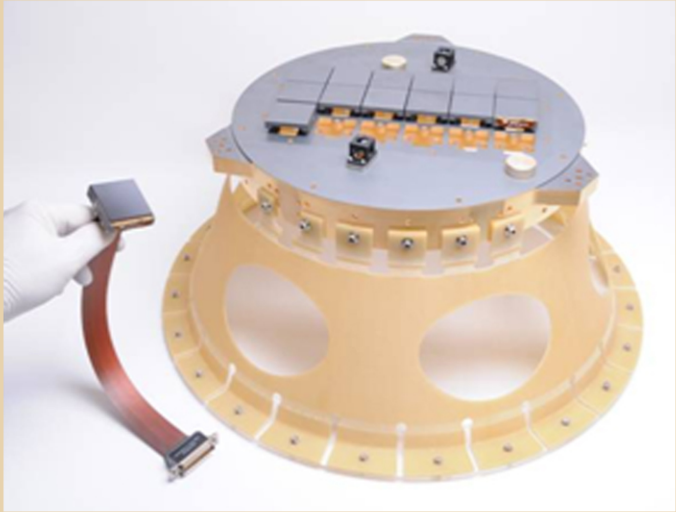

Figure 28. *Photo of mosaic FPA plate that has been assembled with alignment cubes, partially populated with bare SCA packages, and with support structure installed. A single H2RG SCA and flexible interconnection cable are shown at left.*

of the writing of this report, the required cables for SCE electrical interconnection and thermal control have been designed, fabricated, fit-checked, and functionally tested. Operational integration of the characterization facility is in progress. Testing of the FPA is scheduled to begin in September 2011.

PCOS funding was also allocated to design a retrofit of an existing JWST test station called GLS-n. The retrofit is necessary in order to enable the test station to do characterization testing of a WFIRST Detector Module Subassembly (DMS), which consists of a H2RG/SIDECAR™ ASIC SCE pair connected by an electrical interconnection cable. There are two GLS-n cryostats from JWST that will be available to WFIRST. Both of these will be retrofitted as future funding becomes available. These cryostats are required for production-quantity SCA characterization.

Concurrently, WFIRST is developing the H4RG-10, with a format of 4k × 4k × 10-micron pixel pitch, as a science- and cost-beneficial alternative to the H2RG. Smaller pixels reduce the cost per pixel for flight detector subsystems and enable a more efficient optical design for WFIRST. H4RG-10 fabrication is not as mature as H2RG fabrication. Due to the smaller pixels and larger format, it is more difficult to achieve high pixel connectivity via Indium bump interconnects. The PCOS funding has partially enabled critical, non-recurring engineering work in the development of high interconnect yield 4k × 4k × 10-micron format hybrid detector arrays at Teledyne.

Progress, Status, and Plan

The FPA light-shield design incorporates all learning gleaned from finite element modeling of light-shield distortion from thermal and vibrational stresses. Finite element modeling determined the minimum required distance between the light shield and mosaic plate due to the maximum possible deflection of the light shield. In addition, the first vibration mode was computed to be around 2,723 Hz, significantly above the 2,000 Hz minimum requirement.

The EDU FPA characterization facility is nearing completion. The portion of the facility that houses the FPA is in-house at GSFC and has been assembled. Various electrical interconnection and thermal control cables have completed design, fabrication, fit checks, and functional tests. They are ready for operational integration of the characterization facility.

In addition to the EDU FPA characterization facility, PCOS funding was allocated to designing the retrofit of an existing test station to characterize the WFIRST Detector Module Subassembly (DMS), which consists of a H2RG SCA, SCE board, and an interconnection cable.

SCA packages and temperature sensors were placed on order in June 2011. The temperature sensors are in house. However, the procurement of twelve SCAs from Teledyne has been delayed due to unavailability of funding.

On the H4RG-10 front, the processed HgCdTe layers exhibited good performance on the wafer level, as shown by IV electrical tests on process evaluation chips fabricated on the same wafer as the 4k × 4k detector array.

NRE work involved: i) experiments on backfilling 4k × 4k hybrid detectors; and ii) process development on optimizations of Indium bump deposition, hybridization alignment, and hybridization forces required to produce the highest pixel connectivity and lowest shorted pixel population across a 4k × 4k array with 10-micron pixels. The backfilling experiments were performed on existing residual 4k × 4k array assets from another program. The results indicated 100% backfill achieved, as shown by an IR camera. Indium bump deposition process development yielded indium bumps of a different morphology than standard bumps on H2RG (18-micron) pixels, indicating a different nucleation and crystallization mechanism. The indium bumps on H4RG pixels are also not quite as smooth. But the bumps are well defined, and indium bump operability is high in all experiments. It is difficult to know at this stage whether the morphology makes a difference in hybridization performance; this will need to wait for hybridization results.

Efforts are ongoing at NASA to set up a performance test facility for IR H4RG-10 SCAs. This work has started and is planned to be completed in time for the arrival of the parts.

H2RG SCAs

The performance of SiC-packaged H2RG SCAs baselined for WFIRST meets or exceeds current radiometric requirements. In fact, the WFIRST SCAs have the highest performance achieved thus far by HgCdTe detectors in the areas of dark current and persistence. However, there is one issue involving the performance stability and reliability of the detector mounted onto SiC. In particular, dark current and pixel operability may degrade below a certain operating temperature due to microscopic “channel cracks” which appear in the HgCdTe detector layer due to excessive tensile stress on the layer. The tensile stress is significantly larger for HgCdTe films on SiC than on molybdenum due to mismatching of the coefficient of thermal expansion between HgCdTe and SiC. Testing shows that performance degrades in pixels affected by channel cracks.

Preliminary investigation is ongoing to explore the temperature range in which the SiC-packaged H2RG detectors are affected by channel cracks, and to study the behavior of existing cracks when temperature cycled. There are several methods envisioned which would alleviate the channel cracking problem once the cracking mechanisms are determined. All of the methods are feasible from an implementation perspective but would have trade-offs in processing complexity, instrument mass, and possibly performance in other areas. The important point is that the channel cracking issue is solvable with minimal, non-recurring engineering work, with a high likelihood of success, and that early development of the SiC packaging concept has allowed ample time to understand and mitigate this risk.

EDU FPA

Among the challenges anticipated in building and demonstrating a functional N×M mosaic focal plane array of large format infrared detectors, the top ones are: (i) planarity across the entire focal plane array active area; (ii) rework/replacement of individual SCAs in the FPA with minimal impact on the rest of the SCAs; and (iii) thermal uniformity across the entire focal plane array active area.

So far, these challenges have been addressed on the individual SCA level by design and verified by test. The peak-to-valley flatness of each SCA has gotten better with more SCA production experience. The SCA package is designed with modularity and ease of rework/replacement in mind. Thermal uniformity across each SCA is achieved via excellent thermal conduction between the hybrid detector and the relatively thick silicon carbide pedestal upon which it is mounted with an epoxy bondline that is very thin in order to minimize thermal resistance between the hybrid and the pedestal.

The FPA-level challenges so far have been addressed by design and partially verified by test. The mosaic FPA plate is fabricated in the same “flavor” of silicon carbide, and by the same supplier, in order to ensure 100% CTE matching between the SCAs and the FPA plate (Figure 28). Each SCA is serviceable from its bottom side. Vibration testing and thermal cycling of the FPA plate partially assembled with SCAs, bare ROICs, and bare SCA packages have yielded excellent results with regard to stability of components in all directions due to thermal and mechanical stresses.

Technology Development Milestones

Top level technology development milestones and activities:

- Sensor cold electronics (SCE) prototypes: completed by Teledyne on July 1, 2011
- EDU SCE support structure: completed on July 30, 2011
- EDU SiC stray light shield: completed on July 22, 2011
- Initial EDU FPA I&T: August 5, 2011
- Final EDU FPA integration: September 16, 2011
- EDU FPA functional demonstration: September 30, 2011
- H4RG-10 fabrication: completed on August 19, 2011
- H4RG-10 testing 1: completed on October 7, 2011

The twelve H2RG SCA packages are currently on order. The temperature sensors arrived in late June and are available for use.

All EDU SCAs for the mosaic FPA are in house. The EDU FPA light shield completed design in late May 2011, and delivery will take place in early August 2011. With the arrival of the light shield, all components will be in-house. EDU FPA assembly and integration are anticipated to occur in August/September 2011.

Electrical and operational integration of the EDU FPA characterization facility are ongoing and expected to be completed by early September 2011. Basic functional testing and dark response testing of the EDU FPA are scheduled in September to October 2011, and flat-field illuminated testing in November 2011 through January 2012.

Infrared H4RG-10 SCA development started in late 2010 with growth of 4k × 4k HgCdTe layers. Processing of the layers into detector arrays occurred in January through April 2011. Concurrently, non-recurring engineering work started on improving the pixel connectivity across 4k × 4k arrays with 10-micron pixels. Delivery of these devices is expected in July/August 2011.

Planned Activities

Completion of the FPA EDU characterization continues to be a high priority for the Project in order to maintain a good risk posture going into Phase A/B. Plans are in place for this work in FY12, but funding has so far been insufficient to support the planned level of activity.

2.3 IXO/X-ray Technology

2.3.1 X-ray Telescope: Slumped Glass Mirror Technology

Prepared by: William W. Zhang (NASA/GSFC),
Stephen L. O'Dell (NASA/MSFC), and Mark D. Freeman (SAO)

Summary

X-ray telescopes are an essential part of any future X-ray mission. An X-ray telescope's performance, measured in terms of angular resolution and photon collection area, determines a mission's capability and potential for answering existing questions and revealing discoveries that will further our understanding of the universe.

The objective of this development is to mature an X-ray telescope technology that represents revolutionary advances in three key aspects: 1) angular resolution; 2) photon collection area per unit mass; and 3) production cost and schedule per unit photon collection area, measured against the state of the art represented by *Chandra*, *XMM-Newton*, and *Suzaku*, the three currently operating missions.

We have invented a precision glass-slumping technique that replicates lightweight (~1 kg/m^2 of mirror surface area) mirrors at low cost on a short schedule because of its utilization of inexpensive and commercially available, high-quality, thin glass sheets that already meet micro-roughness requirements. The thrust of this technology development program is threefold: 1) to further improve the replication accuracy of the slumping technique to make mirrors of the best possible figure; 2) to develop a set of techniques to align and integrate these mirrors into a housing so that many mirrors collectively form the best possible X-ray images; and 3) to engineer those techniques into a process to build X-ray telescopes that meet technical and programmatic requirements of spaceflight missions.

As of July 2011, we have been able to consistently: 1) make mirrors at 6-arcsec, half-power diameter (HPD, two reflections; the same hereafter); 2) align and bond individual pairs of mirrors to produce X-ray images better than 10 arcseconds, and; 3) demonstrate through finite element analysis and stand-alone environmental tests that a preliminary design of a mirror module based on those techniques can withstand realistic launch loads.

In FY2012, we will continue to refine mirror fabrication, alignment, and integration techniques so that single pairs of aligned and bonded mirrors can achieve X-ray images close to 5 arcseconds. Concurrently, we will use these techniques to align and bond three pairs of mirrors into a medium-fidelity module housing to achieve better than 10-arcsec images. This module will be subjected to a battery of environmental tests, including vibration, acoustic, and thermal vacuum, before a final X-ray performance test to measure its angular resolution and X-ray collection area.

In future years, we continue to execute an existing plan to advance this technology at the system level to a higher TRL for making 10-arcsec telescopes, while refining procedures to achieve better angular resolutions in order to enable a high TRL for sub-arcsecond telescopes before the end of this decade.

Technology Description

Three parameters together determine the intrinsic value of an X-ray optics technology: 1) angular resolution; 2) photon collective area per unit mass; and 3) manufacture cost/schedule per unit photon collection area. Figure 29 shows the first two parameters of three currently operating missions representing state-of-the-art X-ray telescope construction. The approximately diagonal line from the lower-left to the upper-right separates the past and future of X-ray telescope making. The objective of this technology development program is to mature a set of techniques that can build telescopes that reside as far to the lower right in this graph as is possible.

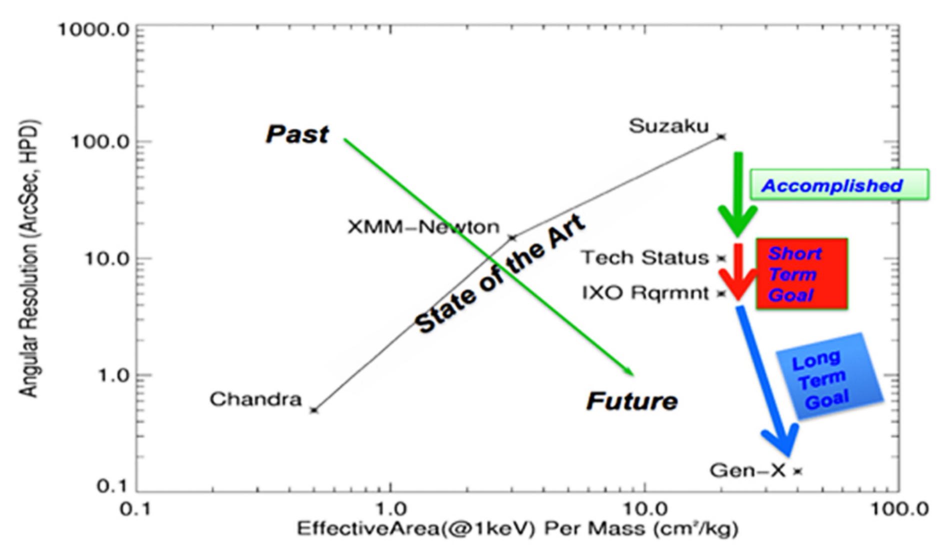

Figure 29. *A graph of two of the three key parameters characterizing an X-ray optics technology showing this technology development effort in the context of currently operating missions: Chandra, XMM-Newton, and Suzaku. The lower-right corner of this graph represents the long-term objective of X-ray optics development for astronomy.*

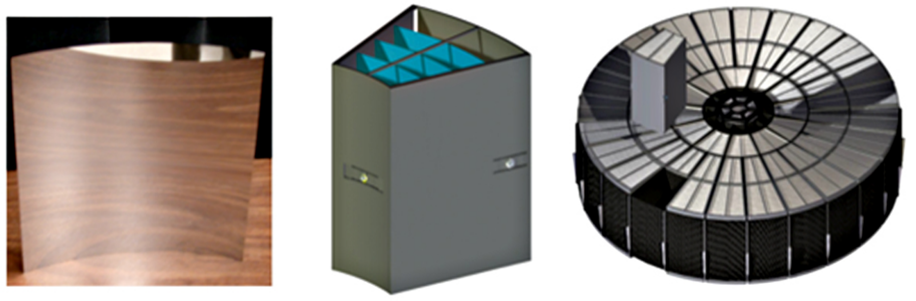

Figure 30. *This graphic illustration shows the process of building an X-ray telescope. It starts with making many very thin mirror segments **(left)**. Typically, on the order of 102 pairs of mirror segments are aligned and bonded into a mirror module **(middle)**. Depending on the size of the telescope, tens to hundreds of modules are integrated to form a single telescope **(right)**.*

A telescope is constructed in three major steps (see Figure 30): 1) fabrication of the mirror segments; 2) construction of the mirror modules, each of which consists of hundreds of mirror segments; and 3) construction of a telescope consisting of tens to hundreds of mirror modules. This technology has three salient characteristics:

1. Through the use of replication, the fabrication of mirror segments is much cheaper than the traditional grinding and polishing method. Each mandrel is typically replicated at least a dozen times. Because the cost of replicating a mirror is negligible in comparison to grinding and polishing, the step reduces the cost by more than an order of magnitude on a per unit mirror area basis.

2. Due to their hierarchical structure, segmented optics are modular and scalable. Thus, they are suitable for making both large telescopes for flagship missions and small telescopes (e.g., Explorer missions). The size of each module is similar in the two cases. The difference between a large and a small telescope lies mainly in the total number of modules needed to be constructed and integrated.

3. Because of its modular structure, with many of its mirror segments and modules being identical, this technology is highly amenable to mass and parallel production. It, therefore, can accommodate a large range in project implementation schedule. It will facilitate project planning by maximizing efficiency while minimizing schedule and cost.

The process of aligning and integrating modules into a telescope is well understood and, as such, needs no further development. Substantially similar tasks have been successfully performed many times for previous missions, such as *Suzuku*, *XMM-Newton*, and *Chandra*.

We divide the technology development effort into areas that can be worked on concurrently to maximize resource utilization efficiency and minimize development cost and schedule.

1. **Forming mandrel fabrication:** Technologies and infrastructure exist in industry and government laboratories to manufacture forming mandrels required for either an Explorer-type mission or for a flagship mission. The purpose of this part of the effort is twofold. The first purpose is to procure as many mandrels as possible in the near term, under a severely constrained budget, for the development of mirror replication techniques. The second purpose is to work with interested industry partners to optimize their process to minimize cost and schedule for manufacturing a large number of mandrels for a spaceflight mission.

2. **Mirror segment fabrication:** This consists of three steps. The first step is to thermally slump thin glass sheets onto forming mandrels to replicate their optical figure while preserving the inherently low micro-roughness of the float glass sheets. The second step is to cut the slumped glass segments to the required dimensions to facilitate their installation into a mirror-module housing. The cutting process must leave behind smooth and fracture-free edges. The third step is to coat the concave surface with a layer of iridium to achieve the maximum possible X-ray reflectivity in the 1 to 10 keV band in a way that minimizes the coating stress on the segments.

3. **Alignment and bonding:** This is the process that integrates a large number of mirror segments into a module. We have two independent and parallel development efforts aimed at the same objective, to reduce development risk. One effort is being pursued at GSFC, and the other at SAO.

The effort at GSFC is a three-step process. The first step is to install the mirror segment in a temporary holder, free of distortion, so that it can be moved and oriented as if it were a rigid body. The second step is to insert the mirror segment into the module housing and align it with other mirror segments to achieve the best possible image and maximum photon collection area. The third step is to permanently attach the mirror segment to the module housing without introducing distortion and then remove the temporary holder.

The Optical Alignment Pathfinder (OAP) technology effort at SAO utilizes multiple sub-micron-level adjustment points on the mirror ends (currently five on each end) to align the optics as well as correct for low-order mirror fabrication errors (absolute radius and cone angle) that are currently not well characterized or easily measured on free-standing optics. The process utilizes mechanical (Coordinate Measurement Machine) and optical (Centroid Detector Assembly) means to determine the mirror net shape and alignment state, and then sub-micron-level actuators to manipulate the mirror. Once alignment is achieved, the manipulated points are bonded to fixed "rails" on the mirror housing.

4. **Module engineering and construction:** Once the necessary techniques to align and integrate mirrors are developed, they are subjected to rigorous engineering analysis, modified and improved where necessary, to ensure that each mirror so attached to the module housing meets all other requirements, such as mechanical structural, thermal, being able to withstand launch loads, and surviving a reasonable range of temperature change. Then a module is constructed and fully tested, both for performance and for environment.

In addition, facilitating each of these development areas is the measurement of the optical figure of the mirror segments at every step of the process. New measurement methods and processes have to be developed and understood to enable the improvement of each of the techniques over time.

Progress, Status, and Plan

Significant progress has been made in each of the technology areas in the past year. We have fabricated a third pair of forming mandrels that meet the original IXO requirement; i.e., 2.5 arcseconds. This accomplishment enables the fabrication, alignment, and integration of three independent pairs into a housing, a necessary condition for completing the demonstration of the next technology readiness level. In 2012, we will continue work with industry partners to mature a mandrel mass production and measurement process for both full-shell and segmented mandrels. Resources permitting, we will sign contracts with one or more companies to polish one or more segmented blanks that have been procured. The completion of these segmented mandrels will enable the demonstration of the mirror fabrication process using segmented mandrels.

We have also made significant progress in advancing slumping techniques. Substrates are consistently made at the 6-arcsec HPD (two reflections) level, with the best mirror substrates having slightly better than 4-arcsec HPD (two reflections). Our plan for FY2012 is to capitalize on the procedures that have produced the best substrates and to understand and develop them into a systematic and reproducible process so that we can consistently make ~4-arcsec mirrors by the end of the year. We have been working with Dr. David Windt of RXO LLC to use a chromium undercoating to ease stress in the iridium layer that has been shown to severely distort the finished mirror segment. Using small coupons, Dr. Windt has demonstrated that the net stress on the Cr-Ir bi-layer film can be nearly zero. In the coming year, we will work with Dr. Windt to coat two-dozen pairs of full-size mirror pairs to confirm that the bi-layer coating meets requirements.

Most notable is our progress in aligning and bonding mirror segments into a housing simulator multiple times and achieving consistent results. Figure 31 shows a pair of mirrors aligned and bonded in a housing simulator installed in a vacuum chamber to be tested in an X-ray beam (left), and a typical X-ray image obtained (right). The long-term stability of such bonded mirror segments is being monitored and tested. Once its long-term stability is established and understood, this process will be used to co-align and bond multiple pairs of mirrors into a housing. We expect to accomplish the stability tests by late 2011 and construct and test at least one three-pair mirror assembly by December 2012.

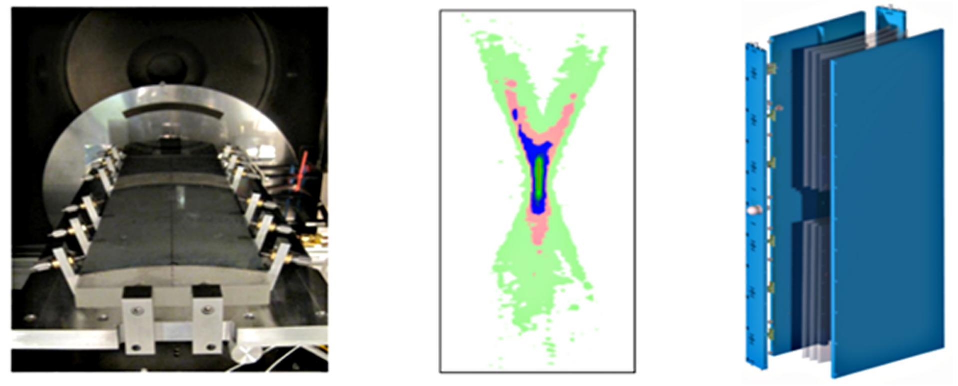

Figure 31. Left: *This image shows a pair of parabolic and hyperbolic mirror segments aligned and bonded onto a module-housing simulator inside a vacuum chamber at the end of a 600-m X-ray beamline.* ***Center:*** *A typical X-ray image from a series of X-ray tests, having the expected bowtie shape with an HPD of 8.7 inches.* ***Right:*** *An expanded view of the mini-module that will be built and tested. A total of three pairs of mirror segments will be co-aligned and bonded into a housing made of KOVAR to match the coefficient of thermal expansion of the mirror segments.*

SAO has twice demonstrated alignment of a single mirror pair in the last year at or near the error budget requirement for a 5-arcsec telescope. In both cases, however, mirror figure has been distorted. Next year's effort will be focused on the reduction of figure distortion to achieve simultaneously good alignment and good figure.

In the area of module design, analysis, and construction, finite element analysis work has demonstrated that the current way of bonding each mirror segment in the housing should allow it to withstand launch loads with adequate positive margins, paving the way for us to build up a module to demonstrate technology readiness at the next level, as shown in the right panel of Figure 31. The module has medium fidelity and will contain three pairs of mirrors that are independently aligned and bonded so that they will focus X-rays to the same point. The module will be subjected to a complete battery of tests: first, X-ray performance tests for its angular resolution and photon collection area; then, vibration, acoustic, shock, and thermal vacuum tests; and, finally, another set of X-ray tests to verify that its X-ray performance has not degraded as a result of the environmental tests. We expect to complete this demonstration for an angular resolution of 10-arcsec HPD (two reflections) by the end of FY12 or shortly thereafter.

Planned Activities

The objective for FY12 is to maintain the development momentum achieved in FY11 to advance this technology for building 10-arcsec telescopes. We envision the following milestones:

1. Conduct experiments to understand the effects of a laboratory environment on aligned and epoxy-bonded mirrors to achieve long-term (~weeks) stability so that multiple pairs of mirrors can be aligned and bonded onto the same housing structure;
2. Co-align and bond multiple pairs of mirrors to form a mini-module for an X-ray test;
3. Co-align and bond multiple pairs of mirrors for both performance and environment;
4. Identify necessary refinements and plausible pathways to making better mirror segments and alignment/bonding techniques to achieve ~5-arcsec HPD that will be pursued in FY2013

2.3.2 Critical Angle Transmission X-ray Grating Spectrometer (CAT XGS)

Prepared by: Ralf Heilmann, Mark L. Schattenburg, and Mark Bautz
(MIT Kavli Institute for Astrophysics & Space Research)

Summary

We describe the technology status, development requirements, and plans for key elements of a Critical Angle Transmission X-ray Grating Spectrometer (CAT XGS). High-resolution X-ray spectroscopy (resolving power $R > 3{,}000$) is essential for progress on a wide variety of key issues in astrophysics, including the nature of and physical conditions in the warm-hot intergalactic medium (WHIM), accretion and feedback processes powered by super-massive black holes in active galactic nuclei, the behavior of matter at super-nuclear densities in neutron stars, and the physics of the interstellar medium in our Galaxy. Diffraction grating technology is the only near-term path to the high-resolution (energies $E < 2$ keV) X-ray spectroscopy required to address these topics. The critical angle transmission grating technology we describe here offers unique and important advantages over other approaches to X-ray grating spectroscopy and has potential applications in missions of all scales from Explorers to flagship observatories.

Following a brief description of the instrument concept and its heritage, we describe the current status of both the XGS grating element and CCD detector technologies and outline the plan and schedule for bringing these to technical readiness for full instrument development.

Technology Description

A CAT X-ray Grating Spectrometer (XGS) is a wavelength-dispersive high-resolution spectrometer offering spectral resolution $\lambda/\Delta\lambda > 3{,}000$ (FWHM) and effective area, depending on the size of the X-ray optic, ranging from hundreds to thousands of cm^2 in the X-ray spectral band at energies $E < 2$ keV. A reference concept incorporates arrays of objective transmission gratings that intercept a portion of the converging beam from an X-ray optic and disperse the X-rays onto a CCD detector array.

The CAT XGS relies on a novel optical element recently developed at MIT: the critical angle transmission (CAT) grating. The CAT grating is a blazed X-ray transmission grating that provides high-dispersion spectroscopy with excellent efficiency over a broad spectral band with low mass and relaxed alignment tolerances (Heilmann et al., 2008). The most recent accounts of the CAT XGS optical principles, state of development, and configuration are given by Heilmann et al. (2011b, 2011a, 2009).

The CAT XGS concept evolved directly from the *Chandra* High-Energy Transmission Grating Spectrometer (HETGS). Developed at MIT, HETGS has been operating successfully since the launch of *Chandra* in 1999. The transmission geometry is highly insensitive to grating alignment and figure errors and, therefore, translates the sharp imaging resolution of *Chandra* into equally sharp spectral resolution[1]. However, HETGS' efficiency is limited by absorption in the grating bars and substrate, and its resolving power is limited by the dispersion of its 200 nm-period gratings, since most X-rays are detected in low (1st) diffraction order.

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[1] The alignment and figure tolerances for reflection gratings are much more demanding than those of HETGS or CAT XGS.

Blazing, which is often implemented with reflection gratings, can channel diffracted power for shorter wavelengths into higher orders and, therefore, leads to higher spectral resolution. Efficient blazing over a broad wavelength range is best achieved for soft X-rays by reflection at small (grazing) angles of incidence. Because X-rays traverse mostly vacuum, grazing incidence reflection also minimizes absorption. The CAT grating combines the advantages of both transmission and reflection gratings, as is illustrated in the left panel of Figure 32.

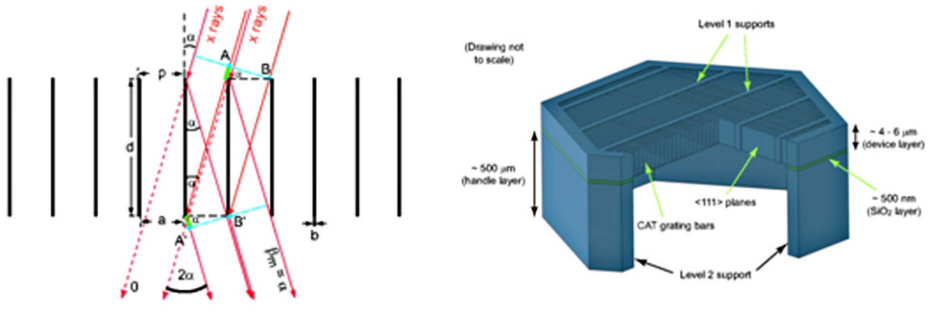

Figure 32. Left: *Schematic cross section through a CAT grating. The mth diffraction order occurs at an angle* β_m*, where the path length difference between AA' and BB' is* $m\lambda$*. In the case shown,* β_m *coincides with the direction of specular reflection from the grating bar side walls (*$\beta_m = \alpha$*); i.e., blazing in the m*th *order.* ***Right:*** *Schematic of a hierarchical CAT grating structure, fabricated on a silicon-on-insulator (SOI) wafer.*

X-rays are incident onto the thin, ultra-high aspect-ratio grating bar side walls at an angle α below the critical angle for total external reflection, θ_c. Every X-ray incident upon the space between grating bars undergoes a single reflection. The optimum grating depth (d) is $d = a/\tan\alpha$, where (a) is the space between two adjacent grating bars. The grating bar thickness (b) should be small in order to minimize absorption or blockage of X-rays. The grating bar sidewalls need to be nm-smooth or better to minimize scattering losses. For soft X-rays θ_c, which is energy dependent, is typically on the order of 1–5 degrees.

The grating equation describes the relationship between the angle β_m at which the mth diffracted order is observed, the wavelength λ of the light incident at angle α, and the grating period (p), $m\lambda/p = \sin\alpha - \sin\beta_m$, with $m = 0, \pm1, \pm2, \ldots$. Note that, so long as $\beta_m < \theta_c$, good diffraction efficiency and resolving power are achieved in higher orders at shorter wavelengths.

We have produced prototype CAT gratings using nanofabrication techniques on silicon-on-insulator (SOI) wafers. The grating structure is shown schematically in the right panel of Figure 32. Grating bars are formed in the 6 μm-thick device layer of the SOI wafer. The grating bars are supported by a two-level mesh structure. A fine mesh is fabricated along with the grating bars in the device layer, and a second, coarser mesh is produced in the handle layer as shown schematically in the right panel of Figure 32 Our prototype gratings have the required grating period (~200 nm), grating bar duty cycle (b/p < 20%) and unprecedented grating bar aspect ratio (d/b = 150) for a flight instrument, and we have measured X-ray performance close to expectations. The status of our development program is discussed in more detail in the next section.

A notional CAT XGS instrument is shown schematically in Figure 33. Arrays of CAT gratings are located behind a portion of a grazing-incidence X-ray mirror assembly. The gratings are mounted tangent to the Rowland torus and diffract X-rays through a range of angles near the grating blaze angle. The dispersed spectrum is recorded by a dedicated CCD camera at B, displaced from the mirror focus F. Thus, the complete CAT XGS instrument consists of a set of grating arrays and a readout subsystem. As noted above, the CAT grating has high diffraction efficiency in many (up to 10) orders near the blaze angle, and the intrinsic energy resolution of the CCD detectors is used to separate the overlapping orders. This configuration leaves ample space at the telescope focus (F) for an imaging detector, but such a detector is not required by a CAT XGS.

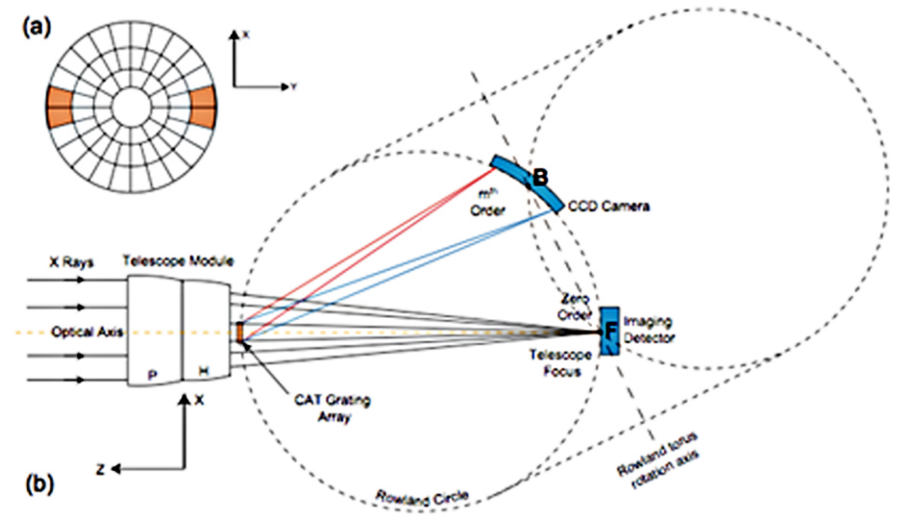

Figure 33. *Schematic of a CAT X-ray grating spectrometer.* ***a)*** *View of the X-ray mirror from the telescope focus. In this case, only a small fraction of the mirror area (shaded) is covered by the gratings.* ***b)*** *Schematic of optical design (not to scale). X-rays are focused by the mirror to the focus F. CAT gratings intercept a fraction of the X-rays and diffract them predominantly at angles centered around the blaze direction. Representative paths for longer (red) and shorter (blue) wavelength rays diffracted in one order are shown. Diffracted X-rays are detected and order-sorted by a CCD camera aligned to the Rowland circle. This configuration leaves ample room for an imaging detector (not required by the CAT XGS itself) at the telescope focus.*

CAT XGS Heritage

X-ray transmission gratings have a long flight history that dates to the *Einstein Observatory*, which operated in the 1970s. As noted above, the CAT XGS is a direct descendant of *Chandra's* HETGS spectrometer, which has been operating successfully since launch in 1999. The MIT group that built the HETGS grating array for *Chandra* is developing the CAT XGS grating membranes and grating array.

The X-ray CCD detectors required for the CAT XGS also have a rich flight heritage, having flown on at least six high-energy astrophysics missions since their first use on the ASCA satellite launched in 1993. CCDs very similar to those developed for, and now operating on, both *Chandra* and *Suzaku* will meet the requirements of the CAT XGS.

Progress, Status, and Plan

We have fabricated CAT grating prototypes with periods of 574 nm (e.g., Heilmann et al., 2008) and 200 nm (e.g., Heilmann et al., 2011a) with anisotropic wet-etching of lithographically patterned <110> silicon-on-insulator (SOI) wafers in potassium hydroxide (KOH) solutions. As noted above, prototype gratings with the required period (200 nm), bar-thickness (40 nm), and bar aspect ratio (150:1) have been successfully fabricated using this process. X-ray tests show that these devices perform at 50% to 100% of the ideal expected diffraction efficiency (Heilmann et al., 2011b). A scanning electron micrograph of one such test article is shown in the left panel in Figure 34.

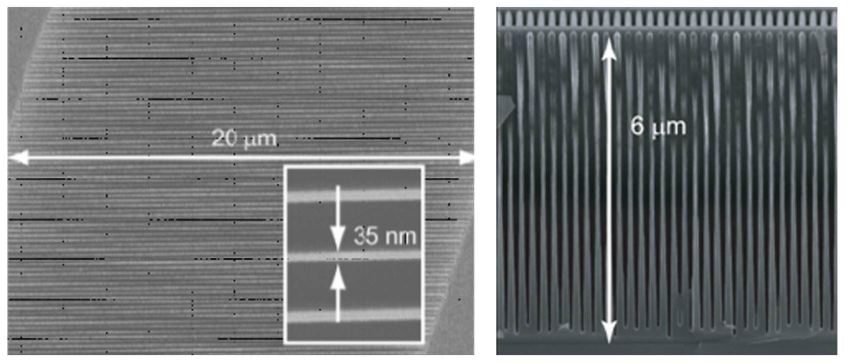

Figure 34. *Scanning electron micrographs of recently fabricated CAT test gratings are shown. The grating bars have the required period (200 nm), depth (6 microns), thickness (35–40 nm), and aspect ratio (150:1).* ***Left:*** *A prototype grating produced with wet-etch process, used in tests that showed expected X-ray performance.* ***Right:*** *A grating fabricated with DRIE process incorporating an integrated Level 1 support mesh is shown. Two L1 supports are visible as vertical planes normal to grating bars.*

It remains to develop an integrated grating-bar support structure that provides an open area of 80% to 90% in a grating facet of the required size (~6 cm diameter). We are investigating use of Deep Reactive Ion Etching (DRIE) to achieve this goal. A recent test article, incorporating the grating and its Level 1 support structure, is illustrated in the right panel of Figure 34. Open areas of >80% appear to be feasible with this approach (Heilmann 2011b). Work has also begun to develop Level 2 grating support structures and to integrate these with the Level 1 support mesh and the grating bars. We have produced test structures with mesh duty cycles as small as 5%. Level 2 structures have also been combined with grating support structures, but further work is required to integrate the required processing on both sides of the grating wafer without damaging the grating bars.

The CAT XGS CCD detectors are modified versions of devices currently operating on *Chandra* and *Suzaku*. These CCDs have the X-ray detection efficiency and spectral resolution required for the CAT XGS. Like all X-ray CCDs, they require optical blocking filters (OBF) to reject out-of-band “optical” (i.e., ultraviolet, visible, and near-infrared) radiation which would otherwise degrade detector performance. These filters absorb X-ray photons as well, reducing system throughput. Sensitivity to optical light can be minimized (and X-ray detection efficiency maximized) by reducing the CCD integration period, since this minimizes the number of incident optical photons per readout for a given optical flux. For the CAT XGS, we will increase the CCD readout speed, reduce the minimum integration time, and thus reduce the required OBF thickness. To further minimize OBF thickness, we will deposit the filters directly on the CCDs.

We have demonstrated prototype (3mm × 3mm breadboard) gratings with measured efficiency at 50–100% of analytical predictions. For application to CAT XGS, current CCD detectors, quite similar to those flying now, suffice.

Technology Development Plans

The remaining challenges for CAT XGS grating technology development are: 1) to perfect grating fabrication techniques to produce Level 1 and Level 2 support structures with larger open areas (approaching 90%) while achieving the required area; 2) to develop a final wet-etch polish for gratings produced with the DRIE process and to demonstrate the expected X-ray diffraction efficiency and spectral resolution; 3) to develop a metal frame to hold each grating facet, develop techniques (like those we used for *Chandra*/HETGS) to align individual grating facets, and demonstrate a breadboard grating array that accommodates launch loads and functions in an operational environment; 4) to enhance the CCD detectors and readout subsystem to maximize low-energy detection efficiency.

The CAT-XGS detector development steps remaining are as follows: 1) develop and demonstrate a directly deposited optical-blocking filter compatible with our high-performance, back-illuminated CCDs; 2) enhance detector readout speed, while maintaining acceptable readout noise, by i) strapping charge-transfer electrodes to reduce conductivity, and ii) equipping the on-chip amplifiers with a (previously demonstrated) low-noise JFET amplifier.

Technology Development Milestones (subject to funding availability)

- Integrated grating with grating bars and both support levels produced: end of Q3 2012
- Wet-polish developed and verified with X-ray test: end of Q2 2013
- Facet frame and grating integrated and alignment procedure developed: end of Q3 2013
- Grating array alignment verification and environmental test: end of Q1 2014
- Verify direct filter deposition on detectors: end of Q3 2013
- Demonstrate high-speed readout: end of Q2 2014

Planned Activities

- Continue development of integrated grating, L1 and L2 supports (Astronomy and Physics Research and Analysis (APRA)-funded)
- Begin grating wet-polish development (APRA-funded)
- Begin CCD filter deposition development (subject to pending SAT proposal)

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2.3.3 Off-plane X-ray Grating Spectrometer (OP-XGS)

Prepared by: Randall McEntaffer (University of Iowa)

Summary

The purpose of the OP-XGS is to provide high spectral resolution, $\lambda/\Delta\lambda > 3000$, and high effective area, >1000 cm^2, at low energies 0.3–1.0 keV. This represents more than an order of magnitude increase in effective area, together with an increase of approximately an order of magnitude in resolving power, over previous observatories. This huge increase in performance will open up new discovery space and, in particular, will address key scientific questions such as:

- Measurements of the WHIM
- Velocity distributions; e.g., in AGN outflows
- High-resolution line emission from stellar atmospheres and plasmas

Here we describe a reflection grating concept known as the Off-Plane X-ray Grating Spectrometer (OP-XGS) (McEntaffer et al., 2010). The design utilizes an array of gratings in the off-plane configuration and a CCD camera for the readout. The technologies are very similar to those utilized for *XMM-Newton* and also have heritage in suborbital rocket missions.

Technology Description

The instrument consists of an array of reflection gratings in the off-plane mount that intercepts a small portion of the main telescope beam and diffracts the light onto an array of dedicated CCDs. The off-plane configuration is capable of meeting the instrument performance requirements at any position along the optical axis from just aft of the optics (focal length = ~19 m) to just a few meters away from the focal plane. This parameter space has been studied in depth to achieve an optimal configuration for the IXO spacecraft design, in which the grating array is placed 5.16 m from the focal plane via the use of a lightweight structural tower.

An example layout is shown in Figure 35. The OP-XGS comprises a grating array mounted upon a rigid, lightweight tower, which itself is mounted on the instrument platform. The tower can also serve as the support for the baffle for the on-axis instruments, providing some saving in system resources. The length of the tower can be tuned to meet the observatory design. The grating array diffracts a portion of the beam (approximately 10%) into several arcs, or spectra, into a fixed CCD camera. The camera is mounted on the instrument platform and consists of an array of CCDs with associated electronics, thermal control and radiation, stray light, and contamination shielding.

The Grating System consists of a Grating Array made from six separate, yet identical, modules, as shown on the bottom left detail of Figure 35. These grating modules are mounted to the top of the Grating Tower, along with an independent thermal control system. Each of the six modules contains 23 gratings that differ only by their width and are co-aligned to form a single spectrum per module. The grooves on these gratings lie nearly parallel to the direction of the incoming X-rays (the off-plane mount) and exhibit a radial, blazed, high-density profile that allows them to obtain high throughput and high resolution. A key element in the instrument design is the detailed layout and groove specification of the gratings themselves. The fabrication of the gratings is achieved through an industrial process that has been well established and, therefore, represents a low risk and manageable technology development/ procurement.

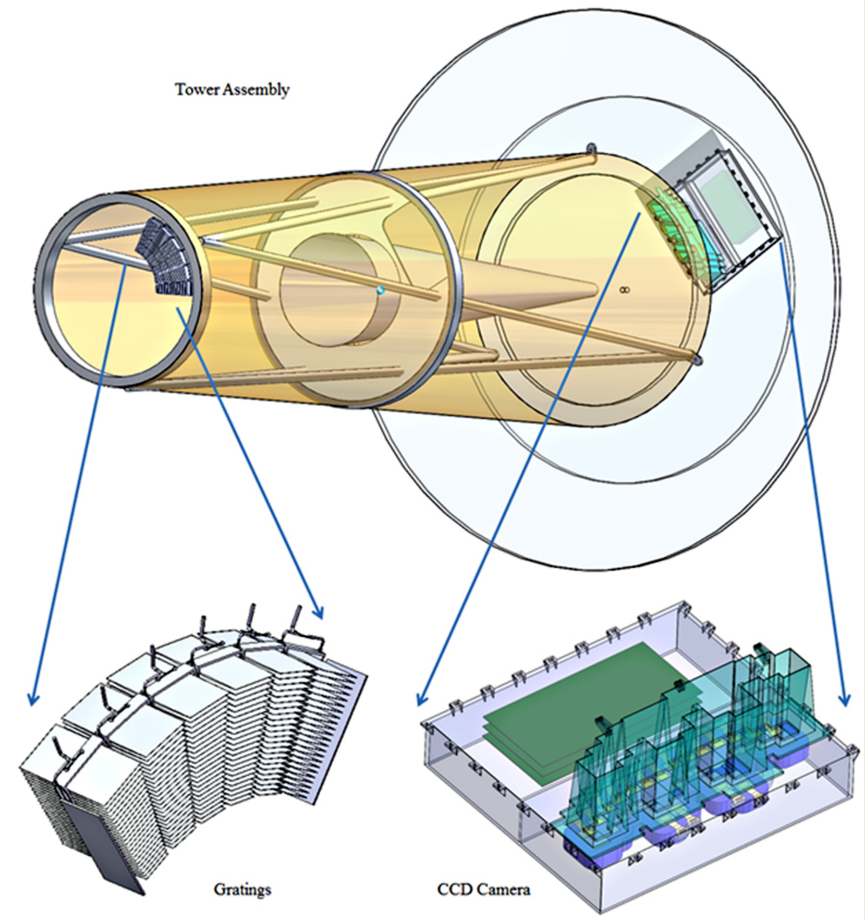

Figure 35. *A schematic of the OP-XGS concept design is shown. Six grating modules are placed on a tower assembly extended from the instrument platform, which also houses the readout CCD camera.*

The CCD camera draws upon the significant heritage of the X-ray cameras that are successfully employed on XMM RGS and EPIC, and *Chandra* ACIS. Due to the spectra having very high resolution, it is not possible to superimpose the outputs of the six grating modules onto a single spectrum. Instead, we project six separate spectra onto the CCD camera. The overlapping spectra provide a high degree of redundancy in the design, where individual CCDs or their drive electronics can be lost without significantly impacting the science data return.

A number of advantages arise from the off-plane geometry in this configuration:

- Meets the science requirements with flexibility to accommodate changes in observatory performance as the spacecraft design evolves
- Meets the A_{eff} requirement of >1,000 cm^2 in the 300–1,000 eV band and exceeds the requirement at other energies—average A_{ef} across bandpass >1,500 cm^2
- Has extended performance out to 1,500 eV due to the efficiency of the gratings and CCDs at the higher energies
- Meets spectral resolution requirement with >20% margin and resolutions upward of 7,000
- No scatter into focal plane instruments
- Compact camera design reduces mass requirements
- Large depth of focus enables focusing by observatory without additional focusing mechanism
- The tower structure provides a convenient and mass-efficient means for integration of other IXO components such as common baffle and particle deflectors for focal plane instruments
- The system is multiply redundant in the six individual spectra projected onto the camera, the electronics concept, CCD array, and thermal control systems

A strength of the design is that it is underpinned by relatively mature technology for the key components of gratings and CCDs. This design ensures a high TRL for the OP-XGS instrument, which in-turn will help ensure delivery on-time and to-budget. The grating consortium is academically-led from institutes with a strong track record in such instrumentation (Universities of Iowa and Colorado in the U.S., and Open and Leicester Universities, plus MSSL in the UK) and is backed by industrial collaborators with strong space heritage (Northrop Grumman and *e2v* technologies).

Progress, Status, and Plan

Off-plane gratings have flown on a number of suborbital missions (Oakley et al., 2011; McEntaffer and Cash, 2008) and provide heritage for the design presented here. Furthermore, the grating substrates, grating modules, alignment technique, and CCD camera are very similar to those used for XMM. To date, the technology development specific to IXO has concentrated on meeting the efficiency and resolution requirements for the gratings. A combination of analytical predictions, extensive ray tracing, and laboratory demonstrations show that the design is capable of obtaining these performance requirements.

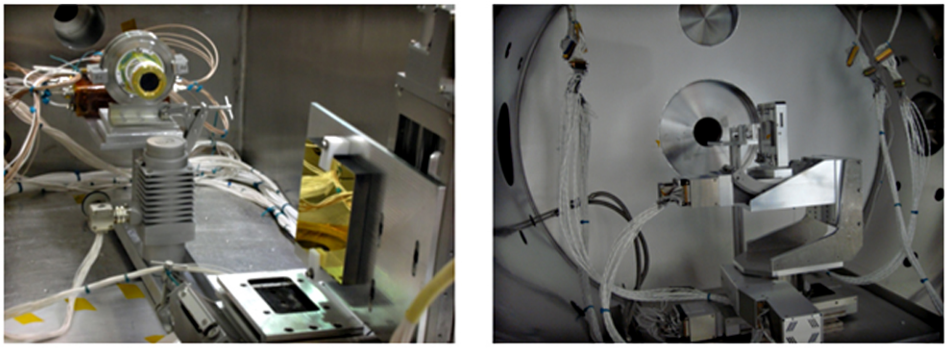

Figure 36. Left: *This image shows a test grating in the University of Colorado X-ray Test Facility.* ***Right:*** *A test grating in the University of Iowa Facility is shown.*

Theoretical calculations of grating efficiency performed independently by the grating manufacturer, Horiba Jobin-Yvon, and our team give expected efficiencies at the 50% level, sum of orders. Using a radial, blazed, high-density prototype grating, we have empirically obtained grating efficiencies >40%, thus approaching theoretical. The current design provides >1,000 cm^2 of effective area from 0.3–1.0 keV, assuming a 40% grating efficiency. An example of the efficiency testing facilities is shown in Figure 36.

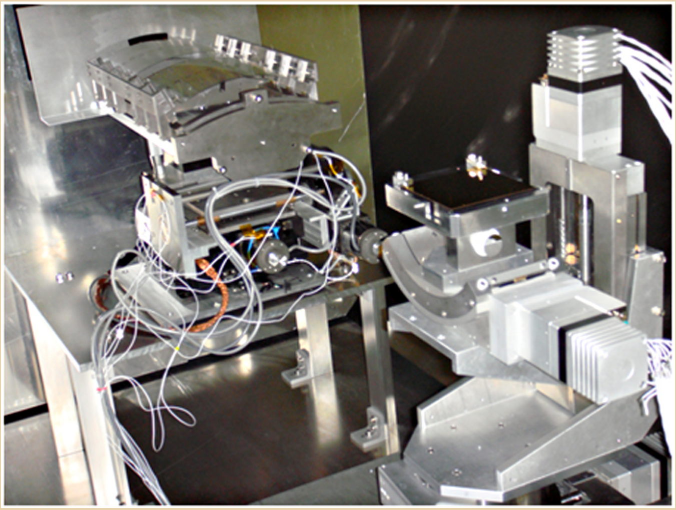

Figure 37. *The MSFC Stray Light Facility large vacuum chamber with test optics is shown. In the upper left of the image, a single parabola and hyperbola are held in a kinematic mount. The test grating apparatus is located on right side of the image with 4-axis motion control.*

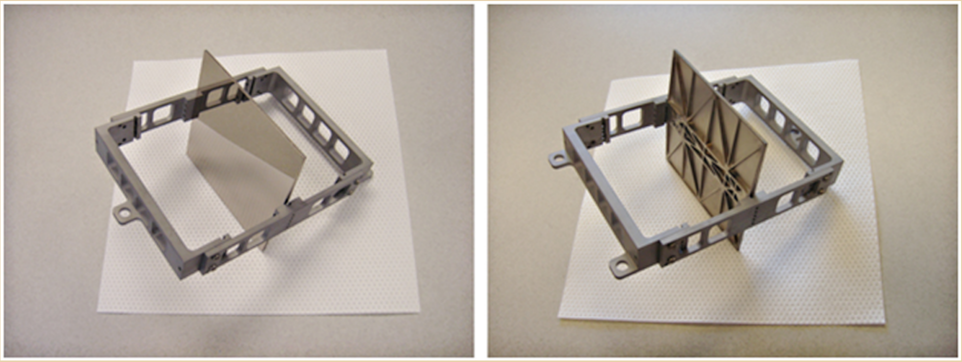

Figure 38. *This image shows a high-fidelity Be grating substrate assembled with a Be grating module mount.* ***Left:*** *The lightweighted back side is shown.* ***Right:*** *The polished, reflective surface is shown.*

Ray-trace analysis of the design gives a theoretical resolution of 9,000 ($\lambda/\Delta\lambda$) at 1 keV in 3rd order. Using a radial, blazed grating, we have empirically achieved a resolution of >200 at 1 keV with a 3-arcmin telescope. Extrapolation to a 5-arcsec telescope gives a spectral resolution of 7,200, well above the requirement of 3,000 over the bandpass. An example of an off-plane grating in a resolution test setup, complete with GSFC slumped glass Wolter optics, is shown in Figure 37. This configuration, along with a soft X-ray CCD camera (not shown), was recently used in testing at NASA's MSFC Stray Light Facility.

All tests have been performed in a relevant environment in terms of temperature and pressure with X-rays, but vibration tests have not yet been performed.

Development has continued in structural modeling and fabrication. Specifically, high-fidelity grating substrates and grating module mounts have been fabricated. Figure 38 shows an assembly of a single grating substrate in a module mount. All parts shown have precision machined Be, providing a lightweight, stiff assembly with no CTE mismatch. The grating substrates have a polished Ni surface with a $\lambda/4$ figure and <1 nm roughness. The substrate profile is trapezoidal and lightweighted on the back, as seen on the right side of the image. These substrates are very similar in form and function to those in the XMM-RGS. The proposed OPXGS concept design incorporates identical substrates in terms of material, size, mass, and surface quality. The module design provides SIX degrees of freedom for manipulation of the gratings. This prototype design allows for THREE gratings to be aligned. Alignment protocols, metrology, and testing are the next steps in module technology development.

Planned Activities

The two key technology development efforts for the OP-XGS will be in grating fabrication and optical filtering of the CCDs.

The grating fabrication development begins with the fabrication and testing of a flight prototype grating master. The grating will have a radial groove profile with high-density, blazed gratings. X-ray efficiency and spectral resolution verification tests on this master, and replicas of the master, are necessary to show the next higher level of technology demonstration. Replicas will be imprinted onto medium-fidelity grating substrates. Efficiency testing will be performed at the University of Iowa, with resolution testing in the Stray Light Facility at NASA's Marshall Space Flight Center.

The technology demonstration requires environmental and X-ray testing of a replica in a medium-fidelity grating mount. Verification of performance and alignment pre- and post-environmental testing will be key steps in achieving the next higher level of technology demonstration. The demonstration of an aligned high-fidelity grating module will be required for flight implementation. The component fidelity will be increased for the groove profile, grating substrates, grating module mount, and alignment technique. Several replicas (3–5) will be aligned in a module. Efficiency testing of this assembly, as well as pre- and post-environmental resolution and alignment testing, will be key steps. In addition, we will fabricate a prototype tower structure for use in these alignment tests.

The CCD filter technology development plan includes the following steps. The first step is procurement of a set of filters/CCDs from *e2v* technologies. The detail of the procured filters is to be determined but may include CCDs in which half the active area has a filter applied and half is without. A subset of these CCDs will be set aside for long-term storage/stability tests. We define successful testing at room temperature and cryogenic testing under vacuum as achieving a demonstration of an even higher level of technology. In practice, these test results may be conducted in a single step (i.e., under vacuum at -80°C).

The test CCDs/filters will be tested at a CCD level for broadband attenuation to optical light, thus performing an A/B comparison for the coated and uncoated halves. The filters will be tested as a function of wavelength at facilities such as NPL, UK. The modeled X-ray transmission at soft X-rays will be confirmed using testing at a facility such as BESSY/PTB. Successful experimental demonstration of key performance parameters will be tested at (or close to) room temperature. The CCDs will then be subjected to environmental testing, including representative thermal (i.e., -80°C) tests under vacuum for low noise performance, thus providing a repeat of the optical/X-ray testing, mechanical testing, as well as results of the long-term storage exercise. The key item for long-term storage would be to check for a change in the thickness of the aluminum oxide on the filter, which would alter the optical and X-ray transmission properties.

References

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McEntaffer, R. L., & Cash, W., "Soft X-ray Spectroscopy of the Cygnus Loop Supernova Remnant", The Astrophysical Journal, 680, 328-335, 2008.

Oakley, P., McEntaffer, R. L., Cash, W., "A Suborbital Payload for Soft X-ray Spectroscopy of Extended Sources,"

2.3.4 X-ray Microcalorimeter Spectrometer (XMS) Technology

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Summary

Future X-ray astrophysics missions require imaging spectrometers with very high spectral resolution, quantum efficiency, focal-plane coverage, and count-rate capability, combined with the ability to observe extended sources without spectral degradation. The X-ray microcalorimeter offers the best performance when considering all of these challenging requirements at once, and its design flexibility allows a myriad of different optimizations within this parameter space. The *Astro-H Observatory*, scheduled for launch in 2014, and a variety of future mission concepts, including AXSIO and *Generation-X*, all feature microcalorimeter arrays as the primary detector technology.

The calorimeter spectrometer instrument of the *Constellation-X* mission concept was named the X-ray Microcalorimeter Spectrometer (XMS). This name has persisted through several *Constellation-X* redesigns, the merger of *Constellation-X* and XEUS to form the *International X-ray Observatory* (IXO), the scaled-down version of IXO (ATHENA) under study by ESA presently, and the parallel NASA effort to scale down IXO (AXSIO). Detailed technology roadmaps were developed for the XMS of both *Constellation-X* and IXO, the most recent and most detailed of which was produced in the summer of 2010. Given the outcomes of the NAS Decadal Review of Astrophysics and the Cosmic Visions process, the technical requirements for XMS are now considerably less well defined. Consequently, the next XMS roadmap has to serve two purposes. It needs to promote the technology readiness of the simpler instrument by de-emphasizing lower TRL components that are now absent in the down-scaled XMS; however, the longer time scale also dictates that it should facilitate the integration of new technologies with the potential for instrument simplification and enhancement down the road.

In what follows, we describe the XMS detector-system baseline and its technology development plan as defined for IXO, noting changes made for ATHENA. The IXO Phase A study selected the *Astro-H* cooling chain as its baseline; by definition, this requires no technology development outside of the *Astro-H* program itself. While a myriad of other cooling chain options exist, discussing these is beyond the scope of this document.

Technology Description

The reference design for the IXO/XMS detector system consists of a composite array of close-packed transition-edge sensor (TES) X-ray calorimeters read out by SQUID multiplexers. Mo/Au TES thermometers with Bi/Au thermalizing X-ray absorbers comprise the arrays. A 40 × 40 central array, arranged on a 0.3 mm pitch, is contained within a 52 × 52 array of 0.6 mm pixels. In the outer array, 4 pixels are read by a single TES, and discrimination between the four positions is achieved via pulse-shape analysis. The outer array contains 576 TES thermometers, compared with the 1,600 of the inner array. In the baseline time-division multiplexing (TDM) concept, 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. The reference design is based on 32-row multiplexing. Heat sinking of the frame of the arrays to the 50 mK stage is achieved via gold wire bonds to gold-coated areas on the array frame, into which heat from the underlying substrate is coupled. Heat sinking within an array is achieved via incorporation of a metallic grid.

For ATHENA, a 32 × 32 array arranged on a 0.25 mm pitch is baselined, and there is no outer array. The scale of the multiplexing has been reduced to 16-row TDM. Dropping the outer array and reducing the size of the inner array, while also decreasing the multiplex scale, doesn't save much in terms of mass and power for the electronics. The main benefit stems from the reduced complexity and size of the focal-plane assembly and greater margin on performance. Other options for simplified instruments include reducing the counting rate, which allows an increase in the multiplexing scale, and this could, in turn, be used to enable a larger array.

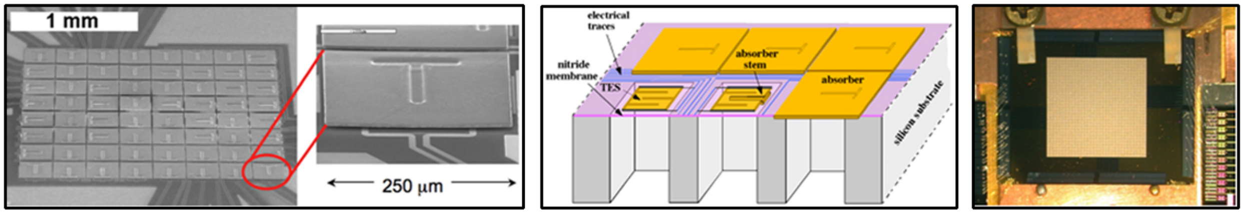

Figure 39. Left: *An electron micrograph of a Goddard uniform TES array with Au absorbers is shown. The close-up view on the right shows an individual pixel. The absorber is cantilevered over the underlying substrate everywhere except in the T-shaped contact area.* ***Center:*** *A schematic showing the structure of a TES array made in the Goddard style is pictured.* ***Right:*** *A 32 x 32 array with Au/Bi absorbers is shown.*

In March 2008, the integrated XMS detector system successfully demonstrated the multiplexed (2×8) readout of 16 different pixels (in an 8×8 array) similar to what is needed for the XMS reference design[2].

At the pixel level, the design is well in hand. The main challenge at the pixel level is presently process control, which is mainly a matter of allocating sufficient resources to 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. Magnetic contamination of the Bi/Au absorbers led to anomalously high heat capacities until remedied. Control of absorber thermalization properties is an outstanding issue. For the most recent arrays fabricated, the main device parameters realized were close to those intended. However, excess broadening in the absorber (non-Gaussian, pulse-to-pulse variation) resulted in worse resolution than implied by the signal-to-noise ratio. Although a resolution of 3.5 eV was achieved at 6 keV, at 1.5 keV the resolution was 1.8 eV. This result is shown in Figure 40.

At the array level, there is a solid foundation for arrays at the 8×8 scale (including uniformity and thermal characterization), and production of reliable 32 × 32 arrays with high-density micro-strip wiring is becoming routine (Figure 39 shows the baseline array concept developed at Goddard). Concepts for array-scale heat sinking are well defined and are presently under development. The degree of heat sinking needed has been defined and determined to be feasible. The specific multiplexer architecture is based on the TDM used for the 2×8 readout

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[2] Kilbourne CA, Doriese WB, et al., 2008, "Multiplexed readout of uniform arrays of TES X-ray microcalorimeters suitable for Conxtellation-X" (Proc. SPIE, 7011, 701104).

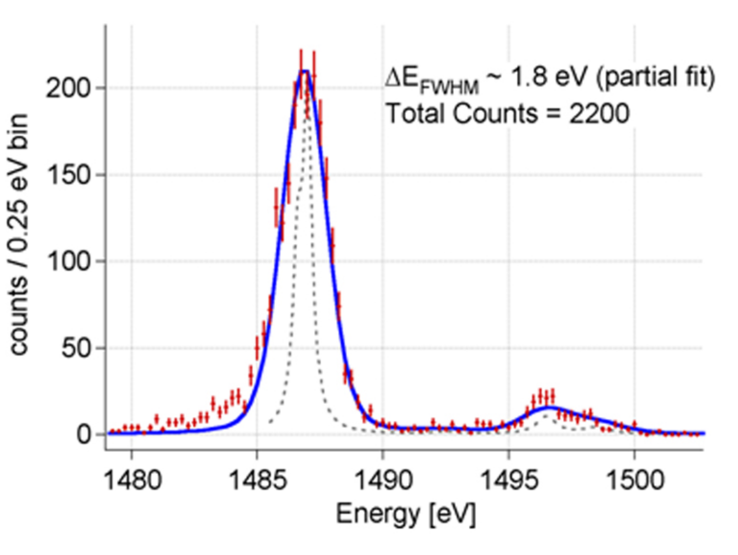

Figure 40. *An Al Kα spectrum showing 1.8 eV resolution achieved on a pixel in a Goddard 32 x 32 array is s hown. A small amount of broadening is apparent. To estimate the full-width, half max (FWHM)of the kernel, the fitting region was set to start at 1486 eV.*

demonstration, with well-defined specific changes implemented to increase the bandwidth, and thus improve and extend the performance of the demonstration to 32 rows. Close to the required bandwidth and noise performance has been demonstrated at the electronics level. Progress has been made in optimizing the noise performance of the test platform. The wide bandwidth (~10 MHz) noise is now believed to be dominated by intrinsic detector and readout noise sources, as opposed to environmental radio frequency pick up. This is critical for large-scale multiplexing of TES arrays. This system will soon be ready for tests with 32 × 32 arrays. Very little work has been done to advance TDM, specifically, in the last year. However, considerable progress has been made on an alternate approach, which is discussed in the next section.

A single TES with six differently coupled 0.3-mm absorbers (a case intermediate between the *Constellation-X* outer-array and the IXO baselined outer array) was tested at Goddard. Resolutions across the 6 pixels ranged from 5.4–7.8 eV. Preliminary work on a TES-based particle veto is beginning to define its materials and design. In the last couple of years, the realization that TES devices are superconducting weak links[3] has led to a deeper theoretical understanding of TES physics. This theoretical framework is guiding the design of experiments that may lead to TES device designs with better energy resolution, resulting in more margin against the XMS requirements.

Thus, the XMS technologies are continuing to advance. New developments (Code Division Multiplexing (CDM) and TES designs based on weak-link physics) promise to enter the mainstream in the near future. A technology readiness demonstration based on the ATHENA requirements is feasible in the next year.

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[3] Sadleir JE, Smith SJ, Bandler SR, Chervenak JA, and Clem JR, 2010, "Longitudinal proximity effect in superconducting transition-edge sensors" Phys. Rev. Lett. 104, 047003.

Technology Development Milestones

The XMS detector system technology development roadmap consists of major milestones tied to significant demonstrations of the integrated detectors and readout electronics, each fed by supporting demonstrations in the detector and superconducting electronics components separately. In this section, we present only the major milestones. For more detailed discussion, please consult IXO-PLAN-001084 REV. – .

XMS Core Array Prototype Demonstration

Demonstrate multiplexed (3 columns × 32 rows) readout of 96 different flight-like pixels on a 0.3-mm pitch in a 32 × 32 (or greater) array with more than 95% of pixels achieving better than 3-eV resolution at 6 keV, when analyzed using a record length and pre-pulse exclusion interval consistent with the requirement of 80% live time at an X-ray rate of 50/s/pixel. The 96 pixels used in this test must span the full range of positions in the array, with respect to distance from the edge of the array. Verification must also be accomplished at count rates up to the equivalent of 50 counts/s/pixel at 1 keV, in those pixels located in a valid test environment (either surrounded by other biased pixels or by unbiased pixels that are shielded from X-rays). Vibration testing of a 32 × 32 array is required to validate the mechanical design of the pixels. **For ATHENA, the technology demonstration has been changed to 3 columns × 16 rows with a resolution requirement of 3 eV, and the 32 × 32 array is to have a pitch of 0.25 mm. The counting rate is presumed the same.**

XMS Outer Array Prototype Demonstration

Demonstrate multiplexed (2 columns × 32 rows) readout of 8×8 array of four-absorber devices (same physical area covered as 32 × 32 core array demo) with better than 15 eV resolution at 6 keV, when analyzed using a record length and pre-pulse exclusion interval consistent with the requirement of 80% live time at an X-ray rate of 2/s/pixel and position discrimination down to energies as low as 150 eV. **For the new XMS, this milestone is either to be deleted or is a placeholder pending establishment of new requirements for the outer array.**

XMS Particle Veto Prototype Demonstration

Demonstrate particle veto prototype on scale appropriate for full XMS array (~36 × 36 mm) 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. **For ATHENA, the anti-coincidence detector size can be much smaller, as the science array is only 8 mm across.**

XMS Detector System Demonstration

Multiplexed (6 × 32) readout of portion of full composite focal plane array—128 different single-TES pixels in a 40 × 40 core array and 64 multi-absorber TES (256 0.6-mm pixels) of a full-sized outer array XMS requirements. A particle-veto has been integrated into the test set-up. Electrical and thermal interconnects and staging are approaching a flight-worthy design, but a flight design is not fully realized. All pixels are biased, although not readout, in order to validate the thermal design. **For ATHENA, the technology demonstration will use 16-row multiplexing, and there will be no outer array.**

Repeating Milestones with Enhanced Technologies

The basic structure of the XMS technology roadmap is independent of the specific implementation of the readout or the array architecture. A promising replacement could be inserted into the flow at any time that it reaches or surpasses the performance of the implementation that it is replacing. CDM developed at the National Institute of Standards and Technology (NIST) will soon replace TDM on the XMS roadmap. CDM's chief distinction from TDM, and its chief advantage, is that all detector pixels are "on" all the time. TDM employs low duty-cycle boxcar modulation functions that switch on and off the TES input SQUIDs one row at a time. By contrast, CDM uses Walsh codes, in which the coupling of the pixel signals is alternated in polarity. Figure 41 shows the 4-pixel Walsh codes and compares them with the TDM modulation. To extract the individual signals, multiplication by the inverse Walsh matrix is required. Because signal is measured from every detector at each sample, instead of once per frame for TDM, CDM has a sqrt(N) noise advantage over TDM, where N is the scale of the multiplexing. The IXO/XMS noise budget was extremely tight, which is the reason the ATHENA resolution requirement was relaxed. Investment in CDM, and its eventual replacement of TDM in the roadmap, will enable more capable implementations of XMS.

Flux-matrixed CDM, which encodes the Walsh matrix in hard-wired coupling to the switched SQUIDs, has been demonstrated as a drop-in replacement for TDM. Using a high-resolution NIST TES array not designed to meet the XMS requirements for pixel size, speed, and fill factor, resolution better than 3 eV on all switched pixels was achieved using flux-matrixed CDM. Thus, CDM is ready for a readout demonstration with an appropriate array. Work is also in progress on switched CDM, which uses superconducting switches to apply the Walsh code.

Planned Activities

The goal for the coming year is to perform a demonstration of an ATHENA-flight-like array at the 3 × 16 scale (3 columns, each with 16 multiplexed pixels) with performance better than 3 eV at 6 keV. This is an essential technology demonstration for ATHENA. The demonstration will be conducted at GSFC, using GSFC X-ray arrays and NIST SQUID multiplexers in an existing test platform. At NIST, this will require the fabrication of SQUID multiplexers with optimized coupling for the GSFC pixels, as well as optimized interface chips and series array SQUIDs. Digital feedback and row-address cards operating at <420 ns dwell times (with a goal of 320 ns) will also be produced. At GSFC, this will require fabricating 32 × 32 arrays at the ATHENA pitch, testing and characterizing them to feed into the optimized interface, and getting the software ready for automated real-time data processing of all the channels. GSFC and NIST will be working closely together on the demonstration and analysis.

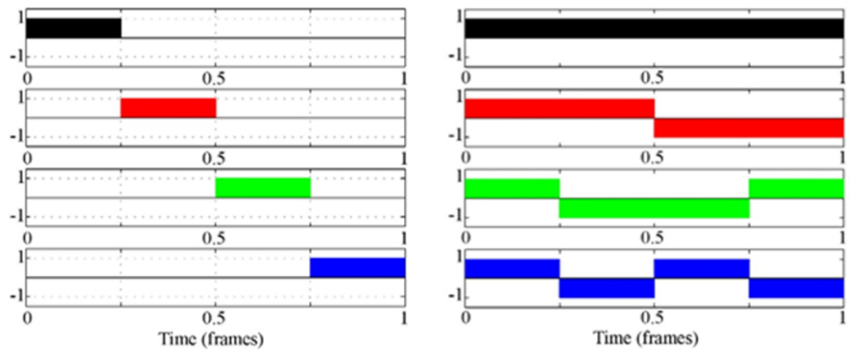

Figure 41. Left: *Modulation functions for four-row TDM are shown. Each pixel is off (in the 0 state) for three rows, and on (in the 1 state) for one.* ***Right:*** *Walsh-code modulation functions for four-row CDM are shown. The polarity of each pixel's coupling is modulated between +1 and -1.*

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SECTION 3.0
PROGRAM TECHNOLOGY NEEDS

As input to the technology development process, the scientific stakeholders are canvassed to provide a summary of perceived technology needs. Input from the scientific community comes through the Physics of the Cosmos Program Analysis Group (PhysPAG), and through an extensive outreach program that targets both meeting venues and potential providers of specific technologies. These inputs are solicited annually, and are provided in the form of a technology needs table. This table is then used by the Technology Management Board (TMB) to prioritize the needs according to a published set of prioritization criteria. The technology needs table, as well as the prioritized list of technology needs, is published each year in the Program Annual Technology Report (PATR).

The TMB used the technology needs tables developed over the summer of 2011 by the PhysPAG's Technology Science Analysis Group (TechSAG). The final version of these tables can be found at the TechSAG website, http://pcos.gsfc.nasa.gov/sags/techsag.php, and in Section 6.0 of this document. However, the final versions were not available as the TMB convened in early September. At that time, draft versions, dated July 25, 2011, were available on the TechSAG website. The TMB evaluated the draft needs tables, and these draft tables are included below (Tables 9–23).

The TechSAG overview table summarizes the mission concepts in roadmap format, with the missions in the columns. For each mission, the general categories of science, mission architecture, wavelength coverage, telescopes and optical elements, detectors and electronics, coolers and thermal control, and distributed spacecraft are described in the rows. Each row is color coded to describe the current technology readiness level (TRL) of that technology (as assigned by PhysPAG's TechSAG).

The PhysPAG's TechSAG also provided specific technology tables for several major mission concepts. These tables provide the detailed technologies needed for a gravitational wave mission (LISA), X-ray mission (IXO), and inflation probe. The technologies for the next generation of missions are summarized: an atom interferometer for gravitational wave detection, atom interferometer for next-generation clocks, hard X-ray mission, EUV/soft X-ray mission, X-ray timing mission, and a gamma ray-Compton mission. In addition, more forward-thinking capabilities (30 years) are described for gravitational wave detection, an ultra-light X-ray telescope, and a gamma-ray-Laue telescope.

For each technology shown in the mission's technology needs tables, descriptions are provided in the following categories:

- **Brief description:** summarizes the key performance criteria for the technology.
- **Goals and objectives:** further details the specific goals of a potential technology development effort.
- **TRL:** specifies the current Technology Readiness Level(s) of the technology.
- **Tipping point:** provides a time-frame during which the technology can be brought to a level where its eventual viability can be assessed.
- **NASA capabilities:** describes NASA's current capability to implement and/or access the technology.

- **Benefit:** details the eventual impact of the technology to the mission concepts that have identified it.
- **NASA needs:** details specific needs and performance requirements for NASA mission concepts.
- **Non-NASA but aerospace needs:** details specific needs and performance requirements for applications outside of NASA mission concepts and within the aerospace sector.
- **Non-aerospace needs:** details 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:** details the desired availability timeframe for the technology.
- **Time and effort:** estimates the duration and scope of the technology development effort.

Technology Roadmap July 2011 PhysPAG Technology SAG * [Draft - 07/25/11]

	Decadal Survey 2010 (New Worlds New Horizons)					Near Term Push Technologies **					Long Term Push Technologies **			
	WFIRST	**LISA**	**IXO**	**Inflation Probe**	**Fundamental Physics**	**Advanced mm-wave/far-IR Arrays**	**Next Generation Hard X-ray Obs.**	**Soft X-ray and EUV**	**Next generation X-ray timing**	**Next generation Medium-energy γ–ray Observatory**	**Beyond LISA (Big Bang Observer)**		**Beyond IXO (Gen-X)**	**Next generation γ–ray Focusing**
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	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	To directly observe gravitational waves resulting from quantum fluctuations during the inflation of the universe		Observe the first SMBH, study growth and evolutionof SMBHs, study matter at extreme conditions	Signatures of nucleosynthesis in SNR, transients, and other sources
Architecture	Single 1.5 M dia. 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.	High-sensitivity, large-format, multi-color focal planes for mm-wave to far-infrared imaging, polarimetry & spectroscopy	Two wide-field (~130 x ~65deg) coded mask telescopes. Full sky ea. ~ 95min	Focusing optics with high resolution spectrometers based on advanced gratings	large(>3m^2) pointed arrays of solid state devices, with collimation to isolate sources	Single platform designs to measure γ-ray lines	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	0.4 to 1.7 um (TBD)	Interferometer λ= 1.064 um - gravity wave period 10-10,000 sec.	0.3 to 40 keV	1 - 10 mm		30 um - 10 mm	5-30 and 10-600keV	5-500 Angstroms	2-80 keV	100 keV - 30 MeV	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	Wide FOV, ~1.5-M diameter mirror	Classical optical design Surface roughness < lambda/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		Large throughput, cooled mm-wave to far-infrared telescope operating at background limit.	Coded aperture imaging: ~ 5mm thk W & ~ 2.5mm holes; ~0.5mm W & ~0.2mm holes	Gratings, single and multilayer coatings, nano-laminate optics	No optics; source isolation by collimator	Compton telescope on single platform	~ three meter 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
		Alignment sensing, Optical truss interferometer, Refocus mechanism			Coupling of ultra-stable lasers with high-finesse optical cavities for increased stability			Actuators			LISA Heritage	wavefront sensing with cold atoms; large area atom optics	0.1 arcsec adjustable optic	
	Classic telescope structure - HST heritage	Athermal design with a Temp gradient Dimensional stability: pm/sqrt(Hz) and um lifetime, angular stability < 8nrad	lightweight precision structure				~ 5" aspect req. over ~6x~3x~1.5m tel. structures	Arcsecond attitude control to maintain resolution	Moderate accuracy pointing of very large planar array		LISA Heritage	10 W near IR, narrow line	Extendale optical bench to achieve 60 M focal length	Long booms or formation flying
Detectors & Electronics	HgCdTe CMOS (H4RG?)	Laser: 10yr life, 2W, low noise, fast frequency and power actuators Quadrant detector, low noise, 10yr 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 10E-15 precision over orbital period; 10E-17 precission over 1-2 year experiment. Cooled atomic clocks with 10E-18 to 10E-19 precision over 1-2 year experiment.	Very large format (> 10^5 pixels) focal plane arrays with background-limited performance and multi-color capability	1m^2 Si (~0.2mm strips)+~ 6m^2 CZT (~1.2mm pixels); ASIC on ea. ~20x20mm crystal. photon-counting over cont. scan	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	Laser interferometer, ~ ~1kWatt 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	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 10E-8 K variation.	Cooling to 50 - 300 mK	LHP to radiators for -~30deg (Si) and ~-5deg (CZT) over large areas		Passive cooling of pixel arrays	Active cooling of germanium detectors	LISA Heritage	Sun-shield for atom cloud	Cryocooler <100mK with 1 mK stability (IXO Heritage)	Active cooling of germanium detectors
Distributed Space Craft		Spacecraft in separate Keplerian orbits. No formation flying or station-keeping. Low contamination μ-Newton thrusterswith low thrust noise			Applicable as precision timing standard in distributed constellations.			Use low-cost launch vehicles for single payloads with few month mission duration			~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

* Derived and updated from 2005 Strategic Roadmap-8 and Universe Roadmap

** Emerging technologies needed for applications in next decade (near-term push) and beyond (long-term push)

🟩	🟨	🟪
TRL7-9	TRL 4-6	TRL 1-3

Table 9.

LISA Technology

[Draft - 07/25/11]

Name of Technology (256 char)	Laser	Phasemeter system	Alignment Sensing	Telescope	Gravitational Reference Sensor	Thrusters
Brief description of the technology (1024)	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. Lifetime > 10yrs. Shotnoise limited at 1mW laser power above 2MHz. Potential laser types: Diode pumped solid state lasers Diode pumped fiber lasers Extended Cavity diode lasers	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 signals.	Alignment sensing in interferometric space missions like LISA or formation flying missions is required 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. **Gravitational reference sensors are completely missing in the TABS with the exception of the atomic interferometer.**	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 but require more thrust but can also tolerate more noise compared to LISA.
Goals and Objectives (1024)	The goal is to reach TRL 6 in 2015 with a laser system that meets LISA requirements. Frequency Comb has nothing to do with the LISA laser. Low noise or Ultra-low noise is not necessary because of active stabilization. The laser is at the beginning of the optical train and the required modulators, fibers, optical components, etc depend on the laser type. A change to a different laser system later could require a complete redesign of large portions of the optical system.	The goal is to reach TRL 6 by 2015 with the 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. Should be developed with Alignment sensing photodetector.	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 to import the technology to learn as much as possible from the pathfinder. This could raise the TRL well above 6 immediately. Future R&D in this direction has to depend 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	4 TRL is between 4 and 5. Requires now efforts towards space qualification and testing in relevant environment.	5 The phasemeter has been demonstrated but only with single element photodetectors and most of the components are not space qualified.	4. This might just be testing commercially available quadrant detectors and identifying one that meets the requirements.	4 for length and alignment stability 2 for backscatter.	Pathfinder GRS: TRL > 6	Colloids: TRL 6
Tipping Point (100 words or less)	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 (100 words)	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's 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. NSF-funded LIGO research could benefit from progress in this area.	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/Ranking	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. Ranking: iv	The capability to measure noise at the ucycl/rtHz level is essential for the R&D on many other components. Having well tested phasemeter system would enable this work and accelerate the R&D in general. Ranking: iv	Maintaining the relative alignment between multiple components on one spacecraft and between separated spacecraft is essential for LISA and for formation flying missions. Having a sensing system early allows tests of newly developed subsystems and integration tests early on. Ranking: vi	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. Ranking: ii	Yes. 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. Ranking: iv	Formation flying would be a game changer. Thrusters are only a part of this. On going effort.
NASA needs/Ranking	LISA and other laser interferometric missions such as formation flying missions, Grace follow-on Ranking: iv	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. Ranking: iv	Required for LISA and formation flying missions. Having a completely characterized system with ucycl/rtHz sensitivity would meet many NASA needs. Ranking: iv	Would significantly simplify LISA and formation flying missions. Ranking: iv	LISA and LISA-follow on missions depend on it. Ranking: iii	Formation flyer depend on it. Need for LISA solved with pathfinder demonstration except for lifetime. Ranking: iv
Non-NASA but aerospace needs	Formation flying might have commercial and national security applications in the form of smaller satellite missions. Ranking: iii	Formation flying might have commercial and national security applications in the form of smaller satellite missions. Ranking: iii	Formation flying might have commercial and national security applications in the form of smaller satellite missions. Ranking: iii	Formation flying might have commercial and national security applications in the form of smaller satellite missions. Ranking: iii	No non-NASA needs as far as I know Ranking: i	Formation flying might have commercial and national security applications in the form of smaller satellite missions. Ranking: iii
Non aerospace needs	Non. Non space-qualified lasers which meet the requirements are commercially available. Ranking i	Science and Engineering applications. Ranking: iii	Science and Engineering applications. Ranking: iii	Ranking: i	No non-NASA needs as far as I know Ranking: i	Ranking: i
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. Ranking ii.	Technical risk is low. The main challenge is to get the temperature dependent dispersion under control. Ranking ii	Technical risk is low. The main challenge is to get the temperature dependent dispersion under control without reducing bandwidth and area to much. Ranking ii	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. Ranking: ii (although the definitions for the rankings are not really applicable)	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. Ranking iv	Should come as early as possible. The development of many other components depends on the availability of a phasemeter with ucycl/rtHz sensitivity. Ranking iv	Requires phasemeter. Should start before phasemeter development is finished and should be finished 1-2 years after phasemeter is at TRL 6. Ranking: iv	Length and alignment: The current status is sufficient for planing purposes. Tests on real models should start 2017. Backscatter: Start immediately as small effort Ranking: iv	The timing is set by ESA. Ranking: iv	Continuous development.
Time and Effort to achieve goal	3 year collaboration between industry and NASA. Ranking: iii	3 year collaboration between industry, academia, and NASA. Ranking iv	2 year collaboration between academia and NASA, Ranking iv	3 year academia project Ranking: iv	Effort and time depends on form of collaboration with ESA. Ranking: iv (because of ESA lead)	Continuous development.
Comment from me	Clarifies specs in TABS	Not mentioned	Wavefront sensing in TABS08 is more adaptive optics related and not alignment related. LISA cares mainly about maintaining alignment.	Telescopes for multi-S/C interferometric missions have different requirements than big optical telescopes. This is not reflected in the TABS	I don't think NASA needs to do anything in this area right now except make sure that they know how the LISA pathfinder works. And please forget the atomic interferometry for the next 10 years.	It is essentially covered. Maybe not really in the context of formation flying missions. OK, atomic interferometry is a real near term project compared to the quantum vacuum drive proposed in this TABS...

Table 10.

IXO-Like X-ray Telescope

[Draft - 07/25/11]

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
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.
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.
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.
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.
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.
Benefit/Ranking	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.
NASA needs/Ranking	Required for moderate to large collecting area x-ray telescopes.	Required for moderate to large collecting area x-ray telescopes.	Required for spectroscopy of WHIM. 10x resolving power of Chandra gratings.
Non-NASA but aerospace needs	NONE	NONE	NONE
Non aerospace needs			
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
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
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

Table 11.

Table 12.

Technologies for the Inflation Probe

[Draft – 07/25/11]

Technology	Detectors			Optical system	Cryogenic system	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 mature sub-Kelvin coolers appropriate for space.	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 half-wave plate 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.
Benefit/Ranking	The development of large sensitive arrays is a major breakthrough that enables precision cosmology. Ranking: iv.		The control of systematics required for a measurement of primordial B modes is a major breakthrough that enables precision cosmology. Ranking: iv.	Optical system developments will continue to improve the capability of missions requiring strong control of systematic error.	Cryogenic system developments will continue to improve the capability of any missions requiring sub-Kelvin cooling.	The development of advanced arrays would simplify the implementation of the Inflation probe, if the mission schedule allows this development. Ranking: iii.
				Ranking: ii.	Ranking: ii.	
NASA needs/Ranking	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.** Ranking: iv		Pixel optical coupling technologies are candidates for future far-infrared missions such as **SPIRIT**, **SPECs, or SAFIR**. Ranking: iv	Improvements in optical systems will benefit **SPIRIT**, **SPECs, or SAFIR**. Ranking: iv	Developments will benefit any other future satellite mission requiring sub-Kelvin cooling, including **IXO**, **SPICA**, **SAFIR**, etc. Ranking: iv	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.** Ranking: iv
Non-NASA but 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. Ranking ii.					Arrays of sensitive bolometers may have national security applications either in thermal imaging of the earth, or in gamma spectroscopy of nuclear events. Ranking ii.
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. Ranking iii.					Sensitive mm-wave bolometer arrays have applications in remote sensing, including concealed weapons detection, suicide bomber detection, medical imaging, and sensing through fog. Ranking iii.
Technical Risk	The technical risk is medium. Commercial solutions do not exist, but multiple university groups, NASA centers (JPL and GSFC), and federal laboratories (NIST) have extensive capabilities. TRL 5 is within reach, and multiple ground- and balloon-borne instruments will be tested in the next few years. Ranking iv.			Individual elements have technical risk (e.g. AR coatings and polarization modulators). Ranking: ii	Most options have some flight heritage but need to meet system requirements. Ranking: ii	The technical risk is medium, assuming a longer development time is available to develop these technologies from their current readiness. Ranking iv.
Sequencing/Timing	Should come as early as possible. The entire Inflation Probe system is dependent on the capabilities of the sensors. Ranking iv			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. Ranking iii
Time and Effort to Achieve Goal	5-year collaboration between NASA, NIST, and university groups. Ranking iii.				Leverage current development for space-borne coolers.	5-year collaboration between NASA, NIST, and university groups. Ranking iii.

[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.

Fundamental Physics: Atom Interferometer for Gravitational Radiation

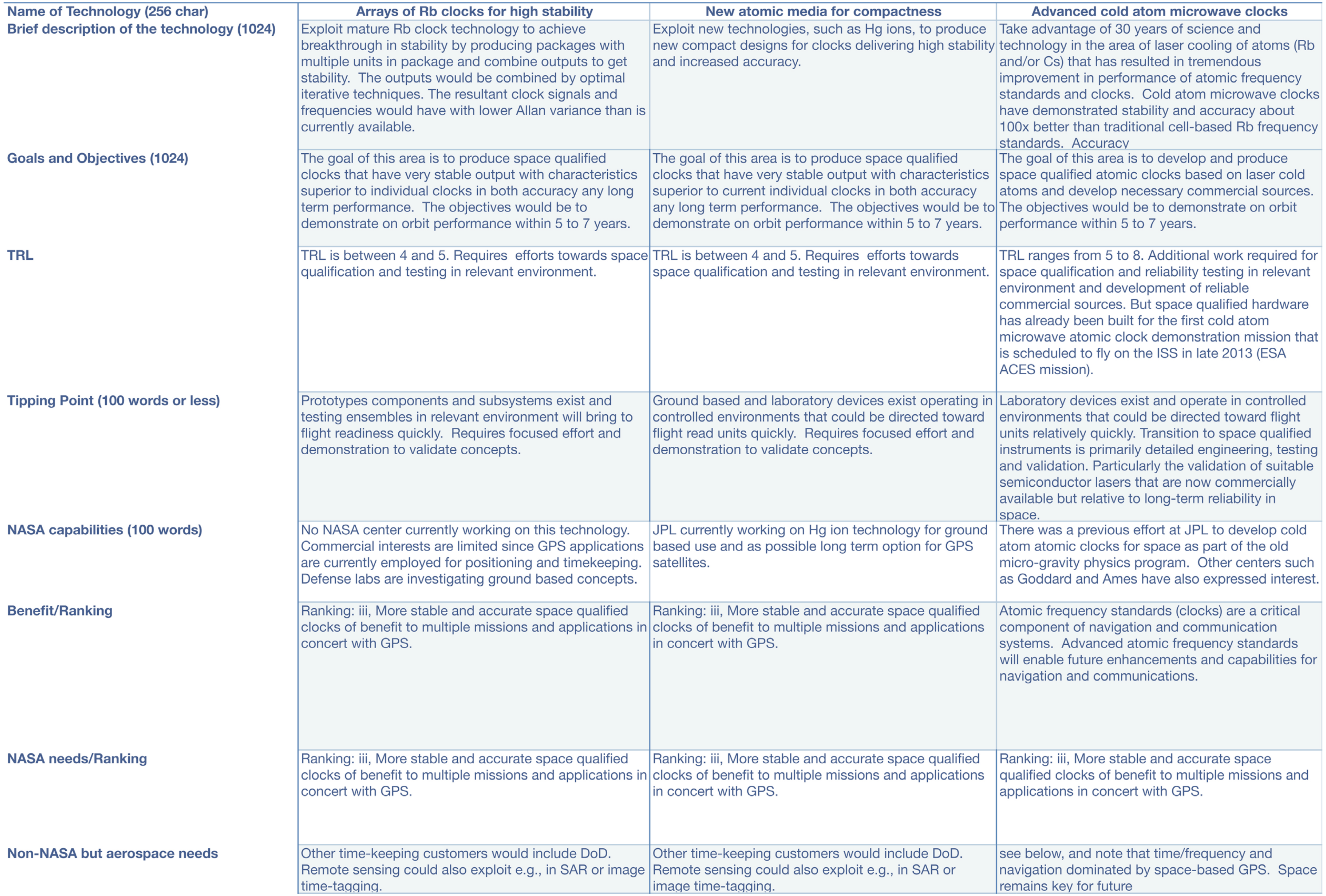
[Draft - 07/25/11]

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	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	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/Ranking	Ranking: iv. 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.	Ranking: iv. 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.	Ranking: iii. The laser source is the essential subsystem for	Ranking: iv. Large booms enable novel space structures.
NASA needs/Ranking	Ranking: iv. High flux atom sources are the core components for precision atom interferometer-based gravity wave antennas, gravity gradiometers and inertial measurement units.	Ranking: iiii. Gravitational wave detection using differential accelerometry is a novel path to meeting identified astrophysics goals for study of coalescing systems.	Ranking: iii. These laser sources are required for atom interferometer-based instruments.	Ranking: iii/iv. Large deployable booms enable atom-based gravity wave antennas.
Non-NASA but aerospace needs	Ranking: ii. These sources are core components for next-generation inertial measurement units. Development for of non-NASA sources currently funded by DoD.	Ranking: ii. Large area atom optics enable accelerometer and gyroscope sensors.	Ranking: ii. Laser sources are core components for atom interferometric sensors.	Ranking: ii. Large, rigid, deployable structures may enable novel DoD systems.
Non aerospace needs	Ranking: iii. Applications to gravitational sensors for geophysics and oil/mineral exploration.	Ranking: iii. Large area atom optics enable compact gravitational sensors for geophysics and oil/mineral exploration.	Ranking: ii. Similar lasers have commercial applications in, for example, remote sensing systems.	Ranking: i. None known.
Technical Risk	Ranking: ii. Technical risk is low. Design principles have been established an validated in design and prototype testing of DoD-relevant systems.	Ranking: ii. Technical risk is moderate. The appropriate techniques have been demonstrated in ground-based laboratory systems.	Ranking: ii. Technical risk is low.	Ranking: i. Technical risk is low.
Sequencing/Timing	Ranking: iv. Should come as early as possible.	Ranking: iv. Should come as early as possible.	Ranking: iv. Should come as early as possible.	Ranking: iv. Should be concurrent with laser and atom source development. System trades depend on size of boom.
Time and Effort to achieve goal	Ranking: iii. 3 year collaboration between industry and NASA	Ranking iv. 3 year collaboration between NASA, academia and industry.	Ranking: iii. 2 year collaboration between industry and NASA	Ranking: iii. 3 year collaboration between NASA and industry.

Table 13.

Fundamental Physics: Next Generation Clocks

[Draft - 07/25/11]



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/Ranking	Ranking: iii, More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	Ranking: iii, 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/Ranking	Ranking: iii, More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	Ranking: iii, More stable and accurate space qualified clocks of benefit to multiple missions and applications in concert with GPS.	Ranking: iii, 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 14.

Fundamental Physics: Next Generation Clocks

[Draft - 07/25/11]

Non aerospace needs	Defense and communciations systems utilize large more complex systems for timekeeping and reliable continuous signal generation.	Use in other communities is primarily for ground based time keeping in major timing centers. Possible application for communications centers	DOD, FAA and as a result the aerospace industry have keen interest in higher performance atomic clocks, time keeping, and navigation infrastructure that can provide higher performance, improved reliability and reduced vulnerability relative to GPS signals. Important for air, space and ground missions in navigation and communication systems.
Technical Risk	Ranking: ii. Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Ranking: ii. Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Ranking: ??. Technical risk is low, although the appropriate semiconductor diode lasers should be validated for long-term reliable operation in space. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.
Sequencing/Timing	Ranking: iv. Should come as early as possible. Development of other system components depends on detector unit parameters.	Ranking: iv. Should come as early as possible. Development of other system components depends on	Ranking: ??. Should come as early as possible. This would be an enabling technology for new space missions and advance navigation and communication system capabilities.
Time and Effort to achieve goal	Ranking: iv. 3 year collaboration between industry and NASA (example of minimal effort)	Ranking: iv. 3 year collaboration between industry and NASA (example of minimal effort)	NASA, plus industry would be the most efficient collaborative effort toward development of cold atom atomic clocks for space.

Table 15.

Next Generation Hard X-ray

[Draft - 07/25/11]

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/Ranking	Ranking: iii. Thick pixelated CZT detectors will provide good position and energy resolution for an unprecedentedly broad energy range.	Ranking: iv. The ASIC is the principal limiting factor for the power budget, energy resolution, time resolution. ASIC performance directly translates into mission performance improvements.	Ranking: ii. Compact active shielding is important for NASA astrophysics missions and can produce reductions in mass and volume.
NASA needs/Ranking	Ranking: iv. 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.	Ranking: iv. 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.	Ranking: ii. Compact active shielding is important for NASA astrophysics missions and can produce reductions in mass and volume
Non-NASA but aerospace needs	Ranking: iii. Space-based monitoring programs in other agencies	Ranking: iii. Space-based monitoring programs in other agencies	
Non aerospace needs	Ranking: iii. Nuclear medicine and ground-based nuclear materials detection applications	Ranking: iii. Nuclear medicine and ground-based nuclear materials detection applications	
Technical Risk	Ranking: ii. Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Ranking: iii. 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.	Ranking: i. Technical risk is low.
Sequencing/Timing	Ranking: iv. 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.	Ranking: iv. ASICS based upon the NuStar ASIC are currently being adapted. Reduced power will be easier to achieve than microvia readout.	Ranking: iv. This concept will be tested in ProtoEXIST 2-3 and compared with existing active shielding concepts.
Time and Effort to achieve goal	Ranking: iv. 3 year collaboration between University, industry and NASA	Ranking: iv. 3 year collaboration betweenUniversity, industry and NASA	Ranking: iv. 3 year collaboration between University, industry and NASA

Table 16.

Next Generation EUV/Soft-X-ray Mission

[Draft - 07/25/11]

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	N ASA has no appropriate facilities but they also exist in other government departments and in industry.
Benefit/Ranking	Ranking iv. 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. Ranking iv.	Gratings and multilayer coatings are essential for normal incidence spectrometers. Fabrication technologies for both are applicable at X-ray and UV wavelengths. Ranking iv.
NASA needs/Ranking	Ranking iv. 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. Ranking: iv	Gratings remain the preferred way to reach high spectral resolution at these energies ranking iv.
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. Ranking ii	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. Ranking iv	Essential to development of explorer class mission
Time and Effort to achieve goal	Ranking iii. Moderate effort. 3 year collaboration between industry and NASA	Ranking iv. Minimal effort. 3 year collaboration between industry and NASA	Ranking iv.Minimal effort. 3 year collaboration between industry and NASA

Table 17.

Next Generation X-ray Timing

[Draft - 07/25/11]

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**
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.
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.
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
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.
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.
Benefit/Ranking	Ranking: iii. 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.	Ranking: iii. The ASIC is the principal limiting factor for the power budget, energy resolution, time resolution. ASIC performance directly translates into mission performance improvements.	Ranking: iii. Older collimator designs are needlessly high in areal density (gm/cm2) 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.
NASA needs/Ranking	Ranking: iii. Pixelated silicon detectors of this type can be applied to various missions that need large area X-ray timing, wide-field imaging, and spectroscopy.	Ranking: iii. 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.	Ranking: iii. Thin, light collimators with good stopping power can be used in a variety of NASA and laboratory settings.
Non-NASA but aerospace needs	Ranking: ii. Such devices might be used in certain envisioned applications such as X-ray navigation of satellites.	Ranking: ii.Such devices might be used in certain envisioned applications such as X-ray navigation of satellites.	Ranking: ii. Collimators might function in flight X-ray systems for applied uses.
Non aerospace needs	Ranking: i. Non space-qualified systems exist to meet non-space needs such as inspections.	Ranking: i. Similar ASICS have commercial applications, but any connection is really via maintaining development teams that can support space and non-space needs.	Ranking: ii. Such collimators could be used for X-ray detector systems on the ground where collimation was a requirement
Technical Risk	Ranking: ii. Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Ranking: iii. 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.	Ranking: iii. 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.
Sequencing/Timing	Ranking: iv. Should come as early as possible. Development of other system components depends on detector unit parameters. Some ongoing development under NASA APRA.	Ranking: iv. 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.	Ranking: iv. Should come fairly early in mission development because it drives overall system characteristics.
Time and Effort to achieve goal	Ranking: iv. 3 year collaboration between industry and NASA	Ranking: iv. 3 year collaboration between industry and NASA	Ranking: iv. 3 year collaboration between industry and NASA

Table 18.

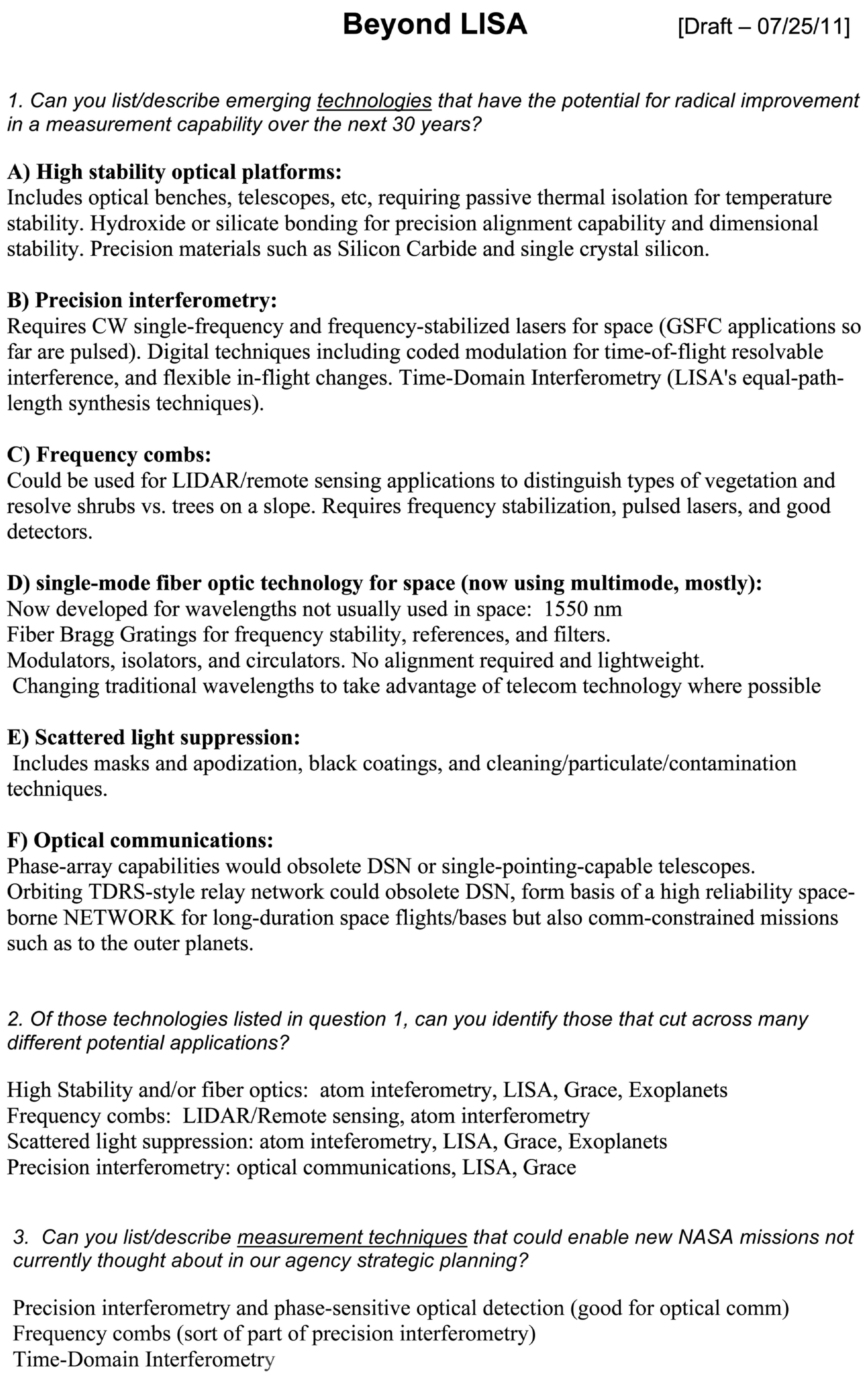
Next Generation Gamma-Ray - Compton

[Draft - 07/25/11]

Name of Technology (256 char)	Si, Ge, CZT or CdTe strip detectors	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.	Low power ASICs are needed to provide accurate energy for each photon but with low aggregate power per square meter.	Germanium arrays need active cooling below 100K, but on the scale needed for a Compton telescope this is a 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 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. 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 between 4 and 5. Primary effort is achieving large scale in heat removal per unit time, followed by 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 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 refrigeration is not achieved, Ge will tend to be eliminated in favor of the room temperature semiconductor options
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.	Refrigeration development capabilities exist in NASA but also in industry.
Benefit/Ranking	Ranking iv.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.	Ranking ii. 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.Ranking: TBD	Ranking iii. Solving refrigeration for this application would conceivably be enabling for other missions
NASA needs/Ranking	NASA needs a next generation medium-energy gamma-ray mission to advance understanding of nuclear astrophysics and black hole sources. Solar physics and lunar prospecting are other applications.	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.	Refrigeration is a general need for germanium detectors in space use
Non-NASA but aerospace needs	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 might have use in sea-level environmental monitoring e.g., for nuclear materials as well as nuclear medicine,etc. Ranking iv	ASICs are an integral part of the system hence contribute similarly to detectors for non-aerospace needs; Ranking iv	
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. Ranking ii	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. Ranking ii	
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. Ranking iv	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	Ranking iv.Minimal effort. 3 year collaboration between industry and NASA	Ranking iv.Minimal effort. 3 year collaboration between industry and NASA	Ranking iii. Moderate effort, 3 year collaboration between industry and NASA

Table 19.

Table 20.



Beyond LISA

[Draft – 07/25/11]

1. Can you list/describe 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 isolation 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.

2. Of those technologies listed in question 1, can you identify those that cut across many different potential applications?

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

3. Can you list/describe measurement techniques that could enable new NASA missions not currently thought about in our agency strategic planning?

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

Gen-X-like Ultra-Light X-ray Telescope

[Draft - 07/25/11]

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/Ranking	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/Ranking	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 21.

Next Generation Gamma-Ray - Laue

[Draft - 07/25/11]

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

Table 22.

Next Generation Gamma-Ray - Laue

[Draft - 07/25/11]

Benefit/Ranking	Ranking ii.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.	Ranking ii. 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.Ranking: TBD	Ranking iii. 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/Ranking	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. Ranking ii	ASICs are an integral part of the system hence contribute similarly to detectors; Ranking iv	
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. Ranking ii	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. Ranking ii	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. Ranking iv	Should come as early as possible. Development of other system components depends on ASIC power performance. Ranking iv	Should come first in mission development because it is a prerequisite
Time and Effort to achieve goal	Ranking iv. Minimal effort. 3 year collaboration between industry and NASA	Ranking iv. Minimal effort. 3 year collaboration between industry and NASA	Ranking iii. Moderate effort, 3 year collaboration between industry and NASA

Table 23.

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SECTION 4.0 PROGRAM TECHNOLOGY PRIORITIES AND RECOMMENDATIONS

The technology needs table discussed in Section 3.0 is the community input for the next step in the process, prioritizing the technology needs. The Technology Management Board (TMB) prioritizes technology needs according to an agreed upon set of evaluation criteria and publishes the results in the PATR annually. PCOS Program staff reference this document as the calls for technology proposals are drafted over the following year.

One of the main functions of the TMB is to prioritize technology needs from the inputs provided by the community. Membership of the TMB includes senior members of the Astrophysics Division at NASA Headquarters and the PCOS Program Office. Subject matter experts, consultants, and internal/external personnel are included as needed.

The Board developed an evaluation method that consists of 11 criteria. These criteria address the strategic alignment, benefits and impacts, risk reduction, timeliness, and effectiveness of each technology. These criteria are summarized in Table 24. For each criterion, a weight is assigned that is intended to reflect the importance that the PCOS Program places on that criterion. These weights may be adjusted from year to year to reflect the changing needs of the Program. Each criterion receives a score of 0 to 4 in the evaluation. The score is multiplied by the established weight for the criterion, and this product is summed across all criteria for each technology.

1. **Scientific ranking of applicable mission concept:** The intent is that a mission ranked highly by a major review process should receive a higher score for its related technologies. The NWNH report is the main source of the ranking for this year. In the future, specific community-based reviews, other peer reviews, or a programmatic assessment may also be considered.

2. **Overall relevance to applicable mission concept:** 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 to the mission concept. This category may be somewhat redundant with some of the more specific categories below, but captures any unanticipated aspects of mission applicability.

3. **Scope of applicability:** If a technology is generally useful to many missions, it is scored higher. For example, optics or detector technologies span more than one mission, whereas an ultra-high-precision timekeeping technology may have more limited applicability.

4. **Time to anticipated need:** If a mission concept is not planned for implementation for a long time, its technologies should receive a lower score than more immediate needs.

5. **Scientific impact:** If a technology improves the scientific return from a mission, then it is scored higher. If it is absolutely required for the mission to be successful, it is scored highest.

#	Criterion	Weight	Score (0-4)	Weighted Score	General Description/Question	4	3	2	1	0
1	Scientific Ranking of Applicable Mission Concept	4	4	16	Scientific priority as determined by the Decadal Review, other community-based review, other peer review, or programmatic assessment. Captures the importance of the mission concept which will benefit from the technology.	Highest ranking	Medium rank	Low rank	Ranking not known	No clear applicable mission concept
2	Overall Relevance to Applicable Mission Concept	4	4	16	Impact of the technology on the applicable mission concept. Captures the overall importance of the technology to the mission concept.	Critical key enabling technology - required to meet mission concept goals	Highly desirable technology - reduces need for critical resources and/or required to meet secondary mission concept goals	Desirable-offers significant benefits but not required for mission success	Minor implementation improvements	Unknown
3	Scope of Applicability	3	4	12	How many mission concepts could benefit from this technology? The larger the number, the greater the reward from a successful development.	The technology applies to multiple mission concepts across multiple 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	Unknown
4	Time To Anticipated Need	3	4	12	How much time is available before the technology is needed to be at TRL6?	4 to 8 years (this decade)	9 to 14 years (early 2020s)	15 to 20 years (late 2020s)	Greater than 20 years (2030s)	Unknown
5	Scientific Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the scientific harvest of the applicable mission concept. How much does this technology affect the scientific harvest of the mission?	Needed for baseline	Major improvement (> ~2x) to primary scientific goals	Only enables secondary scientific goals	No scientific improvements	Unknown
6	Implementation Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the implementation efficiency of the applicable mission concept. How much does this technology simplify the implementation or reduce the need for critical resources?	Needed for baseline	Enables major savings in critical resources (e.g., smaller launch vehicle, longer mission lifetime, smaller spacecraft bus, etc.) or reduces a major risk	Enables minor savings in critical resources or reduces a minor risk	No implementation improvements	Unknown
7	Schedule Impact to Applicable Mission Concept	2	4	8	Impact of the technology on the schedule of the applicable mission concept. How much does this technology simplify the implementation to bring in the schedule?	Technology drives the mission concept critical path	Technology drives the critical path for a key component	Technology drives the critical path for a minor component	Technology is not likely to be on critical path	Unknown
8	Risk Reduction to Applicable Mission Concept Baseline	2	4	8	Impact of the technology on the risk of the applicable mission concept. How much does this technology reduce the risk?	Major mission concept risks directly mitigated by this technology, workarounds not currently known	Major mission concept risks directly mitigated by this technology, workarounds currently known	Minor mission concept risks mitigated by this techology	No risk benefits or technology is already in mission concept baseline	Unknown
9	Definition of Required Technology	1	4	4	How well defined is the required technology? Is there a clear description of what is sought?	Exquisitely defined	Well defined, but some vagueness	Well defined, but some conflicting goals not clarified	Not well defined, lacking in clarity	Poorly defined, not clear at all what is being described
10	Other Sources of Funding	1	4	4	Are there other sources of funding to mature this technology? If funding is expected to be available from other sources, this will lower the prioritization.	No, the Program is the only viable source of funding.	Interest from other sources can be developed during the development time of the technology	Interest from other sources is likely during the development time of the technology	Already being developed by other programs, agencies, or countries.	Unknown
11	Availability of Providers	1	4	4	Are there credible providers/developers of this technology? Where providers are scarce, there may be a compelling need to maintain continuity for the technology in the event there are no replacement technologies.	Single competent and credible provider/developer known	Two competent and credible providers/developers known	Multiple competent and credible providers/developers known	Providers/developers known but no assurance of competence or credibility	Unknown
	Total Possible Score:			100						

Table 24. *Evaluation Criteria for Technology Prioritization*

6. **Implementation impact:** If a technology increases mission implementation efficiency or reduces the need for critical resources, then it is scored higher.
7. **Schedule impact:** If a technology drives mission schedule, then it receives a higher score for development. The intent is to help focus resources during technology development in areas where a technology is perceived to contribute to schedule (and therefore cost) growth during mission implementation.

8. **Risk reduction:** If a technology reduces mission risk compared to the baseline mission concept, then it is scored higher. If the technology is already in the mission concept baseline, then it has no additional risk reduction benefits.

9. **Definition of required technology:** If the required technology is well defined and described, then it is scored higher than vague or inconsistent statements of need. This category again provides motivation for clarity in the identification phase.

10. **Other sources of funding:** A technology that is likely to receive funding from other sources is scored lower than one that has no other potential sponsors. This includes other U.S. agencies and commercial and foreign investments, where they are known. The intent is to focus resources in those areas that need them the most.

11. **Availability of providers:** If there are few providers or a single provider, then the score is higher to maintain this capability as well as to provide resources to potentially enable developing additional providers.

The TMB began the technology needs prioritization process in early September 2011. In order to release this inaugural PATR in a timely manner, the Board used the technology needs table available at that time. This was provided by the PhysPAG in draft form and dated July 25, 2011. This draft technology table is included in Section 3.0.

The TMB identified 75 technologies from the draft version of the PhysPAG technology needs table. During the TMB evaluation process, 13 technologies were determined to be not applicable for evaluation because they were either tied to a mission not in the PCOS program (e.g., WFIRST), considered to be a subset of another technology already on the list, not considered to be a technology for PCOS program development (e.g., spacecraft and launch vehicle technologies), or lacked the definition necessary to be considered for development. Four technologies were combined with other technologies of similar emphasis or objectives. This brings the total number of technologies to 58.

The TMB completed the evaluation process for each of the technology needs. The Board analyzed the rankings to assure that the final results reflect the current strategic thinking and the PCOS programmatic environment. The technology rankings were then categorized into five priority groups, labeled Priority 1 to 5, in order of descending priority. Technologies within any single group are ranked equally.

Table 25 shows the resulting priority groups of the technologies along with their respective science area as identified by the PhysPAG technology needs table.

Priority	Technology	Science
1	X-ray calorimeter: central array (~1,000 pixels): 2.5 eV FWHM at 6 keV; extended array: 10 eV FWHM at 6 keV.	X-ray
	Telescope: Classical optical design. Surface roughness <lambda/30, backscatter/straylight. Athermal design with temp gradient dimensional stability: pm/sqrt(Hz) and µm lifetime, angular stability <8nrad	Gravitational Wave
	Laser: 10 yr life, 2W, low noise, fast frequency and power actuators	Gravitational Wave
	lightweight, replicated x-ray optics. Lightweight precision structure	X-ray
2	High resolution gratings (transmission or reflection)	X-ray
	High-throughput, light, low-cost, cold, mm-wave telescope operating at low backgrounds	Inflation
	Large format (1,000-10,000 pixels) arrays of CMB polarimeters with noise below the CMB photon noise and excellent control of systematics	Inflation
	Phasemeter: Quadrant photodetector: low noise. ADC: 10 yr life, low noise (amplitude and timing). Alignment sensing, optical truss interferometer, refocus mechanism	Gravitational Wave
	µN thrusters: 10 yr. life, low contam, low thrust noise. Not formation flying.	Gravitational Wave
3	Cryocoolers for detectors and other instrument HW	X-ray
	Low CTE materials	Gravitational Wave
	Passive Spitzer design plus cooling to 100 mK	Inflation
	Anti-reflection coatings	Inflation
4	Gigapixel X-ray active pixel sensors	X-ray
	Polarization modulating optical elements	Inflation
	Lightweight adjustable optics to achieve 0.1 arcsec high resolution grating spectrometer	X-ray
	Molecular clocks/cavities with 10E-15 precision over orbital period; 10E-17 precision over 1-2 year experiment.	Fundamental Physics
	Cooled atomic clocks with 10E-18 to 10E-19 precision over 1-2 year experiment	Fundamental Physics
	Cryocooler <100 mK with 1 mK stability (IXO heritage)	X-ray
	Large throughput, cooled mm-wave to far IR telescope operating at background limit	FarIR
	Cooling to 50-300 mK	FarIR
	Very large format (>10^5 pixels) FPA with background-limited performance and multi-color capability	FarIR
	Megapixel microcalorimeter array	X-ray
	High rate Si detector (APS).	X-ray
	passive thermal shielding	Gravitational Wave
	Coupling of ultra-stable lasers with high-finesse optical cavities for increased stability	Fundamental Physics

Table 25. *Technology Needs Categorized in Order of Priority (Technologies within the same priority grouping are ranked equally.) (Page 1 of 2)*

5	Coded aperture imaging: ~5 mm thk W and ~2.5 mm holes; ~0.5 mm W and ~0.2 mm holes	X-ray
	Cooled Ge	Gamma
	Arrays of Si, CZT or CdTe Pixels	Gamma
	1 m^2 Si (~0.2 mm strips)+~6 m^2 CZT (~1.2 mm pixels)	X-ray
	ASIC on each ~20x20 mm crystal	X-ray
	Arc second attitude control to maintain resolution	X-ray
	LHP to radiators for ~-30 deg (Si) and ~-5 deg (CZT) over large areas	X-ray
	Large area atom optics	Gravitational Wave
	Long booms or formation flying	Gamma
	Gratings, single and multilayer coatings, nano-laminate optics	X-ray
	~5" aspect req. over ~6x~3x~ 1.5 m telescope structures	X-ray
	Compton telescope on single platform	Gamma
	1 m precision optics (1/1,000)	Gravitational Wave
	wavefront sensing with cold atoms	Gravitational Wave
	Sun-shield for atom cloud	Gravitational Wave
	Active cooling of germanium detectors	Gamma
	Passive cooling of pixel arrays	X-ray
	Low power ASIC readouts	X-ray
	No optics; source isolation by collimator	X-ray
	ASIC readouts	Gamma
	Laser interferometer ~1 kWatt laser	Gravitational Wave
	extendable optical bench to achieve 60 m focal length	X-ray
	Scintillators, cooled Ge	Gamma
	>3 m^2 Si (or CZT or CdTe) pixel arrays or hybrid pixels -- possibly deployable	X-ray
	10 W near IR, narrow line	Gravitational Wave
	Gravity Reference Unit (GRU) with ~100x lower noise	Gravitational Wave
	Photocathodes, microchannel plates, crossed grid anodes	X-ray
	3 m precision optics	Gravitational Wave
	Active cooling of germanium detectors	Gamma
	focusing elements (e.g., Laue lens) on long boom or separate platform	Gamma
	Megapixel ccd camera	Gravitational Wave
	Thermal stability/control less than 10E-8 K variation	Fundamental Physics

Table 25. *Technology Needs Categorized in Order of Priority (Technologies within the same priority grouping are ranked equally.) (Page 2 of 2)*

The prioritized groups are described as follows:

Priority 1: Contains technologies determined to be of the highest interest and the most compelling to the PCOS Program. These are key enabling technologies for the near-term missions, and they have the strongest technology pull.

Priority 2: Contains technologies of high interest to the Program. These technologies enable near-term missions and have a strong technology pull.

Priority 3: Contains enhancing and general-use technologies that could benefit many missions across the Program.

Priority 4: Contains technologies that enable or enhance a broad range of science themes with various time horizons.

Priority 5: Contains technologies deemed to be supportive of PCOS objectives and mission concepts that are planned for the more distant future.

These groups describe the relative importance of the technologies to the PCOS science objectives and the urgency of the need. Technologies in the higher priority group have higher relative priority, higher technology "pull," and more near-term needs than the subsequent priority groups.

Multiple factors are considered in any selection process, and the priority groups defined in this PATR is only one. As all factors are considered, the Board recommends that the PCOS Program seek to balance the technology investments across the multiple PCOS science objectives and anticipated missions. Finally, the Board is cognizant that investment decisions will be made within a broader context and that other factors at the time of selection may affect these decisions.

After the TMB had finished the prioritization process, the PhysPAG released the final PCOS Technology Assessment for 2011. This final version (Section 6.0, Tables 26-39) included an updated technology needs list, additional supporting information, and an improved format. This final version contains a few additional technologies that were not available or considered during the prioritization process. Notable changes in the final release relative to the draft version include the addition of the following:

- A 21-cm Cosmology Array mission envisioned for the lunar far side. Six associated technologies were described that provide mission capabilities including operation on the lunar far side.
- A high-resolution imaging approach, similar to the NuSTAR architecture, for a Hard X-ray Observatory with associated optics, coatings, and detector technologies.
- Large-area X-ray calorimeter and wide-field detector technologies for the IXO-like X-ray Telescope.
- Three technologies for the Next Generation X-ray Timing aimed at improving sensitivity and collecting area.
- Advanced scintillators and readouts technology for the Next Generation Gamma Ray–Compton mission

SECTION 5.0 CLOSING REMARKS

This Physics of the Cosmos 2011 PATR serves as the first snapshot of the state of technology development under the PCOS Program Office and future directions for technology maturation. The PATR captures the technology needs as identified by the PhysPAG, which are based on community input for science drivers and technology opportunities. The Technology Management Board established rankings for the technology needs. The priorities are intended to serve as the recommendation from the PCOS Program Office to NASA HQ for future technology investments to optimally serve Program goals.

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

The Program Office will continue to interact with the broad scientific community—through the PhysPAG, its workshops, at public conferences, and via public outreach activities—to identify and incorporate the community's ideas about new science and new technology needs in a sustained process. The PCOS Program Office welcomes continued input from the community in developing the 2012 Program Annual Technology Report.

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SECTION 6.0 FINAL TECHNOLOGY NEEDS TABLES

This section contains the final technology needs tables provided by the PhysPAG TechSAG. As described in Section 3.0, the draft versions of these tables were evaluated because the final tables were not ready. The final tables are included here for completeness and reference. These final tables can also be found at the PCOS website: http://pcos.gsfc.nasa.gov/sags/techsag.php.

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

	Decadal Survey 2010 (New Worlds New Horizons)					**Near Term Push Technologies ****						**Long Term Push Technologies ****			
	WFIRST	**LISA**	**IXO-like**	**Inflation Probe**	**Fundamental Physics**	**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**	**Beyond LISA (Big Bang Observer)**		**Beyond IXO (Gen-X)**	**Next Generation γ–ray Focusing**
		Table 1	**Table 2**	**Table 3**	**Tables 4a, 4b**	**Table 3**	**Tables 5a, 5b**	**Table 6**	**Table 7**	**Table 8**	**Table 9**	**Table 10**		**Table 11**	**Table 12**
Science Summary	Study the nature of dark energy via BAO, weak lensing and Snla, 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.	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.	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	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.	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.	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	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		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	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	Wide FOV, ~1.5 m diameter mirror.	Classical optical design; Surface roughness < 1 $\lambda/30$, 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.		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.	~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.
		Alignment sensing, Optical truss interferometer, Refocus mechanism.			Coupling of ultra-stable lasers with high-finesse optical cavities for increased stability.		Hard X-ray grazing incidence telescope with multilayer coatings.	Actuators			Self-deploying magnetic helices	LISA Heritage	Wavefront sensing with cold atoms; large area atom optics	0.1 arcsec adjustable optic	
	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				(5a) 5 arcmin aspect requirement; (5b) 5 arcsec aspect requirement.	Arcsecond attitude control to maintain resolution.	Moderate accuracy pointing of very large planar array.			LISA Heritage	10 W near IR, narrow line	Extendale optical bench to achieve 60 m focal length.	Long booms or formation flying.
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.	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.	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	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.	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.	LISA Heritage	Sun-shield for atom cloud.	Cryocooler <100 mK with 1 mK stability (IXO Heritage).	Active cooling of germanium detectors.
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.			Use low-cost launch vehicles for single payloads with few month mission duration.			Science antennas must be distributed, likely location is lunar far side.	~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 26.

Table 1: LISA Technology

[10/15/11]

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 27.

Table 2: IXO-Like X-ray Telescope

[10/15/11]

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 collabration involving universites, FFRDC and industry.

Table 28.

Table 3: Technologies for the Inflation Probe

[10/15/11]

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 29.

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

[10/15/11]

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 30.

Table 4b: Fundamental Physics: Next Generation Clocks

[10/15/11]

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
Non aerospace needs	Defense and communciations systems utilize large more complex systems for timekeeping and reliable continuous signal generation.	Use in other communities is primarily for ground based time keeping in major timing centers. Possible application for communications centers	DOD, FAA and as a result the aerospace industry have keen interest in higher performance atomic clocks, time keeping, and navigation infrastructure that can provide higher performance, improved reliability and reduced vulnerability relative to GPS signals. Important for air, space and ground missions in navigation and communication systems.
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. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Technical risk is low, although the appropriate semiconductor diode lasers should be validated for long-term reliable operation in space. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.
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	Should come as early as possible. This would be an enabling technology for new space missions and advance navigation and communication system capabilities.
Time and Effort to achieve goal	3 year collaboration between industry and NASA (example of minimal effort)	3 year collaboration between industry and NASA (example of minimal effort)	NASA, plus industry would be the most efficient collaborative effort toward development of cold atom atomic clocks for space.

Table 31.

Table 5a: Next Generation Hard X-ray

[10/15/11]

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 32.

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

[10/15/11]

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 33.

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

[10/15/11]

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 34.

Table 7: Next Generation X-ray Timing

[Draft - 10/15/11]

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 typicaly 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 significat 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 35.

Table 8: Next Generation Gamma-Ray - Compton

[10/15/11]

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 36.

Table 9: 21 cm Cosmology Array

[10/15/11]

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
Brief description of the technology (1024)	LRA science antennas must operate at frequencies below 100 MHz. The expected H I signals cover a large range in redshift, and the larger the bandwidth able to be received, the larger the range in cosmic evolution can be covered. Current ground-based science antennas obtain a frequency dynamic range of approximately 3.5:1. In order to achieve sufficient collecting area, a large number of antennas are required, demanding low mass for an individual antenna. Potential antenna types: Polyimide film-based dipoles Self-deploying helixes	Signals received from the science antennas must be amplified, and potentially bandpass filtered, then digitized. Analog electronics, including analog-to-digital converters (ADCs) that operate on the lunar surface during nighttime. Power required for combined analog and digital components, per antenna, < 100 mW.	After digitization, received signals must be converted to spectra and combined (cross-multiplied from antennas or correlated). This processing must occur on the lunar surface, potentially some of it during nighttime. Power required for combined analog and digital components, per antenna, < 100 mW. A digital correlator for combining the signals will also be required, with power required < 10 kW.	Electronics associated with antennas, or groups of antennas, will require power (~ 100 mW), capable of being generated or obtained during nighttime operation (~ 300 hr sustained) in an environment that is dark and cold (~ 125 K). Power sources and/or energy storage units must be low mass because of the large number of antennas. Power options: High specific capacity batteries Small Radioisotope Power Units (RPUs) Beamed power distribution	Antennas must be distributed over a geographical region ~ 10 km. Rovers must have a high payload/rover mass ratio, capable of sustained traverse speeds (~ 1 m/s), autonomous navigation capabilities, and dexterity to deploy antennas and associated electronics.	Antennas (and electronics) will be distributed over ~ 10 km. Data must be transported from individual antennas, or groups of antennas, to the central correlator. Data rates could exceed 400 Mbps, for as long as 300 hr. Potential options: Wireless radio Fiber optic Laser communication
Goals and Objectives (1024)	Reach TRL 6 by early next decade. Final mass target not needed as prototype system would be fewer antennas.	Demonstrate 4–6 bit, 200–400 Ms/s ADC with a power consumption < 10 mW	Demonstrate 12 nm process with < 1 V supply by late this decade	Demonstrate < 10 W production or capability by early next decade	Demonstrate autonomous navigation at 1 m/s traverse speed by early next decade	Demonstrate sustained > 100 Mbps data rates by early next decade
TRL	3–4. Requires technology selection. Technologies have been tested in field, but not relevant environment. Requires efforts to test in relevant environment, and potentially space qualification, depending upon antenna type		4. 350 nm process with 0.5 V supply at TRL 7. Requires effort to reduce feature size, supply voltage, and demonstrate in relevant environment.	2. Requires technology selection, expanding operating temperature environment, and technology development, depending upon selection.	5. Rovers at TRL 7+. Requires effort to increase payload/rover mass ratio and increase traverse speed.	5. Requires technology selection, and 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 37.

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

[10/15/11]

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 38.

Table 12: Next Generation Gamma-Ray - Laue

[10/15/11]

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 39.

SECTION 7.0 ACRONYMS

ACIS	Advanced CCD Imaging Spectrometer (aboard *Chandra*)
ACTO	Advanced Concepts and Technology Office
A/D	Analog-to-Digital
ADC	Analog-to-Digital Converter
AGN	Active Galactic Nuclei
ANU	Australian National University
APRA	Astronomy and Physics Research and Analysis
ASIC	Application Specific Integrated Circuit
CAT XGS	Critical Angle Transmission X-ray Grating Spectrometer
CCD	Charge-coupled Device
CDM	Code Division Multiplexing
CMNT	Colloid Micronewton Thruster
CFRP	Carbon Fiber Reinforced Polymer
CMOS	Complementary Metal-Oxide Semiconductor
COR	Cosmic Origins
Cs-FEEP	Cesium Field Emission Electric Propulsion
CTE	Coefficient of Thermal Expansion
DDL	Detector Development Lab
DFACS	Drag-Free and Attitude Control System
DMS	Detector Module Subassembly
DRIE	Deep Reactive Ion Etching
DRS	Disturbance Reduction System
ECL	External Cavity Laser
EDU	Engineering Development Unit
EPIC	European Photon Imaging Camera (aboard *XMM-Newton*)
ESA	European Space Agency
FEEP	Field Emission Electric Propulsion
FPA	Focal Plane Assembly
FPGA	Field Programmable Gate Array
FWHM	Full Width Half Maximum
GRS	Gravitational Reference Sensor
GSFC	Goddard Space Flight Center
HETGS	High-Energy Transmission Grating Spectrometer
HPD	Half-power Diameter
HST	Hubble Space Telescope
I&T	Integration and Test
IMS	Interferometric Measurement System
IXO	International X-ray Observatory
JDEM	Joint Dark Energy Mission
JFET	Junction Field Effect Transistor
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LIMAS	LISA Instrument Metrology and Avionics System
LGA	Land-grid Array
LGS	Lucent Government Systems
LISA	Laser Interferometer Space Antenna
LPF	LISA Pathfinder

MOPA	Master Oscillator Power Amplifier
MSFC	Marshall Space Flight Center
NGO	New Gravitational-wave Observatory
NIST	National Institute of Standards and Technology
NPRO	Non-planar Ring Oscillator
NRC	National Research Council
NWNH	"New Worlds, New Horizons in Astronomy and Astrophysics," a report released by the National Research Council
OAP	Optical Alignment Pathfinder
OATM	Optical Assembly Tracking Mechanism
OBF	Optical Blocking Filters
OP-XGS	Off-plane X-ray Grating Spectrometer
PATR	Program Annual Technology Report
PCOS	Physics of the Cosmos
PhysPAG	Physics of the Cosmos Program Analysis Group
PMS	Phase Measurement System
RF	Radio Frequency
RGS	Reflection Grating Spectrometer
RIN	Relative Intensity Noise
ROIC	Return on investment capital
SAO	Smithsonian Astrophysical Observatory
SAT	Strategic Astrophysics Technology
SBIR	Small Business Innovative Research
SCA	Sensor Chip Assembly
SCE	Sensor Cold Electronics
SD	Silicon Diode
SGO	Space-based Gravitational-wave Observatory
SMA	SubMiniature version A
SOI	Silicon-on-Insulator
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SQUID	Superconducting Quantum Interference Device
SR&T	Supporting Research and Technology
ST7	Space Technology 7 (a NASA mission designation)
TDI	Time Domain Interferomery
TDM	Time-Division Multiplexing
TES	Transition-Edge Sensor
TMB	Technology Management Board
TPCOS	Technology Development for Physics of the Cosmos
TRL	Technology Readiness Level
USO	Ultra-stable Oscillator
WFIRST	Wide-Field Infrared Survey Telescope
WHIM	Warm-Hot Intergalactic Medium
XMM	X-ray Multi-mirror Mission
XMS	X-ray Microcalorimeter Spectrometer

Chemical Elements

AuBi	Gold Bismuth
Be	Beryllium
BiAu	Bismuth Gold
Cr-Ir	Chromium Irridium
HgCdTe	Mercury Cadmium Telluride
KTP	Potassium Titanyl Phosphate
LiNbO3	lithium niobate
MoAu	Molybdenum Gold
SiC	Silicon Carbide
Yb	Ytterbium

Units

arcmin	arcminutes
arcsec	arcseconds
cm	centimeters
cm^2	square centimeters
C	Celsius
eV	electron volt
F	Fahrenheit
Hz	hertz
k	thousand
K	Kelvin
keV	kiloelectron volt
kg	kilogram
m	meters
m^2	square meters
mHz	millihertz
MHz	megahertz
mK	millikelvin
mm	millimeters
mW	milliwatts
nm	nanometers
s	seconds
µm	micron (micrometer)
W	watt