PhysPAG/TechSAG PCOS Technology Assessment 10/15/11

The TechSAG has undertaken a task to assess the technology needs for current and future PCOS science objectives. Following approval by the Astrophysics Subcommittee, the results of the assessment will be provided to the PCOS Program Office as input to their Program Annual Technology Report to be used by the Astrophysics Division to guide planning for PCOS technology related activities.

The TechSAG developed a draft technology roadmap and supporting tables to capture the PCOS needs and invited community comment through August 12, 2011. Comments received were assessed and incorporated based on the best judgment of the TechSAG and a final roadmap and set of supporting tables were generated for submission to the APS and PCOS Technology Office.

Notes.

1. Use of "Roadmap". This technology assessment is not intended to prioritize technologies or mission concepts, but rather gather community input on PCOS technology needs. A roadmap form generally organized by mission concept was chosen as a convenient way to identify technologies phased by time. A mission concept provides a specific set of requirements and allows identification of technologies organized around telescopes and optical elements, detectors and electronics and spacecraft. However, the technologies are intended to be applicable for a full range of mission sizes and applications.

2. Roadmap organization. The roadmap is organized into three sections: (a) missions recommended by the Decadal plus Fundamental Physics, requiring technology development in the present decade, (b) near-term “push” mission concepts that require development of emerging technologies starting now and extending into the next decade, and (c) long-term “push” concepts needing emerging technology development into the following decade. We recognize that the Decadal missions are undergoing redefinition, however the technology needs for the science objectives are clear and so are included.

3. WFIRST falls under the Exoplanet Exploration program but covers a number of important PCOS science objectives. For this reason the mission has been included in the roadmap table, but without a detailed technology table.

4. The 21-cm cosmology array science (Table 9) falls squarely under the COPAG scope, however such an instrument would yield important PCOS science and so we have included the science and technology. A discussion of PCOS science has been included following Table 9.

5. Technology Tables. For each column in the roadmap (WFIRST excepted) there is corresponding table or tables with the set of needed technologies. Each column in the technology table corresponds to a different technology. For convenience we have chosen to use the same format developed by the NRC for their recent review of NASA's Office of the Chief Technologist technology road maps. Note that the Inflation Probe table includes technologies for both the Decadal mission and the near-term push technology for advanced mm-wave/far-IR detector arrays.

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 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.	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 λ/30, backscatter/ stray light.	lightweight, replicated X-ray optics.	High-throughput, light, low-cost, cold mm-wave telescope operating at low backgrounds; Anti-reflection coatings; Polarization modulating optical elements.		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 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 2: IXO-Like X-ray Telescope

Name of Technology (256 char)	Thermal formed (slumped) glass mirror segments	Large-scale alignment and mounting of thin glass mirror segments	Gratings for dispersive x-ray spectrometer	Large area x-ray calorimeter	Wide Field Detector
Brief description of the technology (1024)	Thermally form, to precision mandrels, thin glass sheets into Wolter I mirror segments. Includes cutting mirrors to appropriate size, and coating with x-ray reflective material.	Thousands of mirror segments need to be aligned to one another, made confocal, and mounted in a flight housing. Mounting must not distort the mirror figure.	High ruling density off-plane (OP) reflective and critical angle transmission (CAT) x-ray gratings for dispersive x-ray spectroscopy.	X-ray calorimeter for high resolving power non-dispersive spectroscopy coupled with moderate angular resolution imaging. Includes development of calorimeter pixel multiplexing, refrigeration, energy resolution, and field size (total number of pixels).	High-speed silicon imagers with active electronic elements in each pixel and large numbers of parallel readout channels.
Goals and Objectives (1024)	Requirement for perfectly aligned primary-secondary mirror pair are 3.3-6.6 arc-sec HPD for 5-10 arc-sec HPD mission, respectively. Manufactureability requirements drive fabrication yield and fabrication time/mirror segment. Need TRL 6 by 2014 for future mission development.	Alignement requirement for multiple segments and multiple shells is ~ 1.5 to 3 arc sec HPD. Figure distortion due to mounting and alignment must be less than 1.2 to 2.5 arc sec HPD. System must survive launch seismic and acoustic loads. TRL 6 by 2016 for future mission development.	Development of gratings with resolving power lambda/delta-lambda > 3000 over wavelengths of ~ 1.2 to 5 nm. High efficiency required to make use of full resolving power. Many individual grating cells or plates must be coaligned. TRL 6 by 2018.	Develop large format (~ 100 to 1000 sq. mm area) detector with < 2.5 eV resolution. May include smaller pixels in central area and larger, lower resolution (< 10 eV), surrounding pixels. Minimize readout time and increase pixel multiplexing. TRL 6 by 2018.	Achieve CCD-like performance (5 electrons read noise or better, 50 microns depletion depth or better) in a 100mm focal plane mosaic Megapixel imager with kHz frame rates. Need TRL 6 by 2016--2018 for future IXO-like mission.
TRL	Estimate current TRL at 4 - 5. Have achieved ~ 8.5 arc-sec HPD, but have not yet demonstrated manufacturing times required for large area telescopes.	Estimate current TRL at 3. Mirror segment pairs have been aligned and mounted to < 1.5 arc sec HPD. Figure distortion due to mounting exceeds requirements. Have not yet demonstrated alignment and mounting of mirror segments from multiple shells.	Estimate current TRL 4. Single reflective OP gratings have been made but have not yet demonstrated resolving power of several thousand. Lithographically made CAT gratings have also been manufactured, but with insufficient efficiency.	TRL 4. 2.5 eV resolution has been demonstrated over limited number of detector pixels. Multiplexing 8 to 16 pixels has been demonstrated.	Currently at 4 for various different devices..
Tipping Point (100 words or less)	Better than 6.6 arc sec HPD will demonstrate performance for 10 arc sec mission positively rated by ASTRO2010. Process needs to be industrialized to make large scale production credible.	Moderate - alignment requirements met but mounting deformation ~ 5 times too high. Significant development still required.	Modest improvement in resolution will result in meeting science requirements.	10 mm x 10 mm detector area provides large enough area for small field of view telescope.	Moderate. Different device architectures currently meet individual requirements, but no device yet meets all requirements. Need lower noise in hybrid devices and/or deeper depletion in monolithic devices; thus development is still required.
NASA capabilities (100 words)	NASA GSFC leads in development of thermal forming and is fully equipped to continue experimentation.	NASA GSFC and SAO have developed alignment mounting techniques. Alternatives or similar approaches could be developed in optics industry.	NASA does not have capability but development capabiilty exists at MIT, Univ. of Colo., and Iowa State.	NASA has developmetn capabilities, as do other research labs (NIST, MIT), and some European facilities.	NASA does not have this capability. Current commercial CMOS APS devices do not meet X-ray detection requirements, but FFRDC and commercial organizations (e.g. Lincoln Lab., Teledyne, Sarnoff) have development capibilities.
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 3: Technologies for the Inflation Probe

[10/15/11]

Technology	Detectors: Sensor Arrays	Detectors: Multiplexing	Detectors: Optical Coupling	Optical system	Cryogenic system	Push Technology[b] Advanced mm-wave / far-IR Arrays
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.

Computational Requirements

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

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

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

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

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

Table 4b: Fundamental Physics: Next Generation Clocks

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

Table 4b: Fundamental Physics: Next Generation Clocks

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 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	

Table 5a: Next Generation Hard X-ray

Non aerospace needs	Nuclear medicine and ground-based nuclear materials detection applications	Nuclear medicine and ground-based nuclear materials detection applications	
Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Technical risk is moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	Technical risk is low.
Sequencing/Timing	CZT detectors with the required pixel size are currently being adapted from those flown on ProtoEXIST1. ProtoEXIST2 will incorporate 0.6mm pixels over tiled detector for balloon flight test in 2012.	ASICS based upon the NuStar ASIC are currently being adapted. Reduced power will be easier to achieve than microvia readout.	This concept will be tested in ProtoEXIST 2-3 and compared with existing active shielding concepts.
Time and Effort to achieve goal	3 year collaboration between University, industry and NASA	3 year collaboration betweenUniversity, industry and NASA	3 year collaboration between University, industry and NASA

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

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

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

[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

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

Non-NASA but aerospace needs	There is synergy with DoD use of similar LV and satellite systems, creating potential for partnershiops	potential remote sensing applications	potential remote sensing applications
Non aerospace needs	Not applicable, by definition	Can be used in synchrotron and laser plasma research	Can be used in synchrotron and laser plasma research
Technical Risk	Technical risk is low; development paths are straightforward	Technical risk is low but there is some risk of backsliding in the industrial capabilities.	Technical risk is moderate for completely new approach.
Sequencing/Timing	Needed immediately to establish programmatic viability	Should come as early as possible. Development of other system components depends on it.	Essential to development of explorer class mission
Time and Effort to achieve goal	Moderate effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA

Table 7: Next Generation X-ray Timing

Name of Technology (256 char)	Pixelated Large-Area Solid State X-ray Detectors	Low-Noise, Low-power ASICs for Solid State Detectors	Thin, Lighweight X-ray Collimators	Thin, lightweight X-ray concentrators	Point source optimized concentrators .	Lobster eye X-ray optics for All-sky Monitors
Brief description of the technology (1024)	X-ray timing science objectives call for achieving several square meters of X-ray sensitive collection, over range 2-30 keV, obtaining time of arrival and energy for each photon. Silicon pixel arrays, silicon drift detectors, pixel arrays of high-Z materials, or hybrids are possible choices but all need development.	Low power ASICs are needed to provide accurate time of arrival and energy for each photon but with low aggregate power per square meter.	Requirements of new X-ray timing instruments built around solid state elements require re-thinking design of the collimator unit that provides source isolation. In order to not dominate the mission mass and volume budgets, the collimator must be much thinner and lighter than previous honeycomb colllimator designs.	Lightweight concentrators can focus X-ray beams onto small detectors; Concentration allows sensitivity gains of >1000 over pure collimation.	Concentrators optimized to provide large collecting area for much lower mass than 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.

Table 7: Next Generation X-ray Timing

Non aerospace needs	Non space-qualified systems exist to meet non-space needs such as inspections.	Similar ASICS have commercial applications, but any connection is really via maintaining development teams that can support space and non-space needs.	Such collimators could be used for X-ray detector systems on the ground where collimation was a requirement	Concentrators at energies >10keV have medical applications.		This technology has wide application for materials studies and medical imaging.
Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units.	Technical risk is moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	Technical risk is moderate for completely new approaches. Lacking such investment there would be fallback to older designs mis-matched to requirements, resulting in sub-optimized mission performance.	Low	Low	Low
Sequencing/Timing	Should come as early as possible. Development of other system components depends on detector unit parameters. Some ongoing development under NASA APRA.	Should come as early as possible. Development of other system components depends on ASIC power performance. No active US program. Europeans modifying particle physics detectors.	Should come fairly early in mission development because it drives overall system characteristics.	Should come fairly early in mission development.	Should come fairly early in mission development.	Should come fairly early in mission development.
Time and Effort to achieve goal	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA	3 year collaboration between industry and NASA

Table 8: Next Generation Gamma-Ray - Compton

[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;	

Table 8: Next Generation Gamma-Ray - Compton

Technical Risk	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units. Cost risk may drive material preferences.	Technical risk is low. The design principles are generally understood but progress comes through design iterations to refine performance based on completed units. Cost risk may drive material preferences.	Technical risk is low to moderate given access to (rare) analog ASIC design expertise. The history of analogous flight projects shows this task must not be underestimated.The main challenge is to get low power with low noise.	
Sequencing/Timing	Should come as early as possible. Development of other system components depends on detector unit parameters. Only modest programs in Ge and CZT are ongoing.	Should come as early as possible. Development of other system components depends on detector unit parameters. Only modest programs in LaBr3, advanced organics, and SiPMs are ongoing.	ASIC design must be matched to design of the detector element and cannot precede it, but should be roughly simultaneous.	Refrigeration system needs to be designed as part of mission system engineering.
Time and Effort to achieve goal	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	Minimal effort. 3 year collaboration between industry and NASA	to iii. Minimal to moderate effort depending on scale of mission. 3 year collaboration between industry and NASA.

Table 9: 21 cm Cosmology Array

[11/04/11]

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 < 1 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 Systems (RPS) 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 sufficient radiation tolerance and < 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	3–4. Analog components, including digitizers, have flown,	1. Commerical process at 12 cm not available yet; 350 nm process with	2–4. Requires component technology	5. Rovers at TRL 7+. Requires effort to increase	5. Requires technology selection, and

	been tested in field, but not relevant environment. Requires efforts to test in relevant environment, and potentially space qualification, depending upon antenna type	but not designed for extreme environments	0.5 V logic at TRL 9, and 250 nm at 2.5 V radiation hard-by-design (RHBD) at TRL 7 in 2011. Requires effort to reduce feature size, supply voltage, and demonstrate in relevant environment.	selection, expanding operating temperature, and technology development, depending upon selection. Requires system integration design.	payload/rover mass ratio and increase traverse speed.	possible space qualification. Depending upon technology, requires mass reduction and increase in data rate transmission.
Tipping Point (100 words or less)	Antennas have been deployed in the field, but not in a relevant environment. A focused effort could increase this technology to TRL 6 in a fairly short time	Scaling of power consumption with both bit depth and sample rate needs to be improved.	Funding for radiation hard-by-design technology at feature sizes below 90 nm.	Renewed production of Pu for RPS; demonstration of small power conversion technology	Rovers have been deployed on both Earth and Mars, but increases in autonomy and payload-to-rover mass are needed.	
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 developed 2-bit ADCs with GHz sampling rates at several hundred microwatt power consumption	NASA has developed RHBD at 350 nm and 250 nm; via an SBIR program is development of 90 nm RHBD.	NASA has produced multiple generations of radioisotope thermal generators (RTGs) and a Stirling generator (ASRG) is underway	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.
NASA needs	LRA, potential Heliophysics and Planetary Science missions	All NASA missions could benefit from lower power analog components, particularly for digitization.	All future NASA missions could benefit from lower power digital components and system-on-chip afforded by RHBD at 110 nm/90 nm and smaller electronic nodes.	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 on Earth
Non aerospace needs	None.	Mobile devices would benefit from lower power ADCs, though specific designs might	Terrestrial electronics at small nodes have reported radiation susceptibility.	Small RPS-derived technologies could be used for terrestrial remote	Commercial operations in harsh environments	None.

		vary.	Developed technology can potentially mitigate such effects.	power applications.		
Technical Risk	Technical risk limited to obtaining electromagnetic performance at minimal mass. Materials for space-based antennas are well developed.	Technical risk is medium. Fundamental physics is understood for room-temperature ADCs, but ADCs in extreme (temperature and radiation) environments requires development	Technical risk is medium. Low-power digital electronics have been demonstrated in space, but the key RHBD cell technology differs at 90 nm and below. A technology roadmap exists for future development but requires funding.	Technical risk is low. Energy conversion is in hand; thermal input technology flight proven. DOE has managed many system integration contractors.	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, DOE, academia, and industry	7–10 year collaboration between NASA, DoD, academia, and industry	7 year collaboration between NASA, DoD, academia, and industry

H I 21 cm Cosmology and PCOS

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

$$\delta T_b \approx 25 \text{ mK } x_{HI} (1 + \delta) [(1 + z)/10]^{1/2} [1 - T_{CMB}(z)/T_s] [H(z)/(1 + z)/dv_{||}/dr_{||}]$$

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

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

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

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

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

Table 10: Beyond LISA [10/15/11]

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

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

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

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

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

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

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

Technologies that cut across many different potential applications:

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

Table 10: Beyond LISA [10/15/11]

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

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

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

[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 12: Next Generation Gamma-Ray - Laue

Name of Technology (256 char)	**pixelated Ge or CZT detectors**	**ASICS**	**focusing optics**
Brief description of the technology (1024)	High spectral resolution is needed to obtain nucleosynthesis signatures and spatial resolution is needed to isolate sources and maximize signal to noise. In this approach signal to noise is optimized using a focusing optical element in front of the detector array, thereby reducing the total number of detectors but requiring operation at higher count rates. Germanium and CZT have been considered as materials.	Low power ASICs are needed to provide accurate time of arrival and energy for each photon but withability to handle higher counting rates produced by focusing	Science objective is achieved in a set of narrow energy bands but with high signal to noise in those bands achieved using focusing optics
Goals and Objectives (1024)	The goal is to reach TRL 6 in 2015, to meet opportunities for near-term explorers	The goal is to reach TRL 6 by 2015	The goal is to reach TRL 6 by 2015
TRL	TRL is 4 for CZT or Ge. Requires efforts towards space qualification and testing in relevant environment.	TRL is essentially undefined until the detector is specified. The ASIC is specific to the detector and developed in co-evolution with it.	TRL is 4.
Tipping Point (100 words or less)	Designs have reached TRL 4. A focused effort could increase this to TRL 6. A few cycles of fabrication and test are realistically necessary, but must be coordinated with ASIC development.	Pixel designs require custom ASIC development to meet targets for power combined with noise level.	If a breakthrough in optics is not achieved, the preferred option will be Compton telescopes meaning larger array dimensions but without optics
NASA capabilities (100 words)	NASA's capabilities support test but strip arrays are custom procurements from commercial sources.	NASA has engineering groups producing custom ASICs at GSFC but suitable groups also exist in DoE or at commercial sources.	N ASA has no special facilities but they exist in other government departments, industry, and elsewhere, with choice of source depending on requirements and approach
Benefit	The detector array is the primary factor determining system performance, setting the size scale, sensitivity and other factors, enabling the entire mission concept, hence the science.	Detector capability alone without an ASIC suitably matched to it could lead to prohibitive system power and make the concept unworkable. Multiple turns of development are likely needed.	Producing optics for this application would be largely mission specific and not transferable to other uses, but the optical solution is enabling for this approach to a medium gamma-ray mission.

Table 12: Next Generation Gamma-Ray - Laue

[10/15/11]

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