Astronomy and Physics (Code SZ)

Enabling Technologies for Future Missions the Origins and SEU (Structure and Evolution of the Universe) Themes

February 22, 2004

Melvin Montemerlo (HQ) <mel@nasa.gov>

Editor: John Hong <John.Hong@jpl.nasa.gov>
Contributors: James Breckinridge (JPL/Origins), Rich Capps (JPL), Michael Devirian (JPL), Jennifer Dooley (JPL), John Hong (JPL), Ron Polidan (GSFC), Juan Roman (GSFC), Chris Schwartz (GSFC/SEU)

Contents:

PURPOSE AND CONTENTS OF THIS DOCUMENT

The purpose of this document is to provide a single source for all of those interested in the enabling technologies/capabilities required by missions which are listed either in the Roadmaps of the two themes, Origins, and Structure and Evolution of the Universe (SEU), or in the Vision Missions NASA Research Announcement (NRA) of the Office of Space Science.

Any attempt to list "future technology requirements" must have specific limits or it will grow too large to be useful. Therefore, this document is limited to those missions which are already included in the Strategic Plans / Roadmaps for the Origins and SEU themes. The reference documents are:

- *Origins: 2003 – Roadmap for the Office of Space Science Origins Theme)*
- *Beyond Einstein: from trhe big bang to black holes*. January 2003

This document was intended to be limited to those missions which are not yet in Phase A. For now, a few missions which are already in Phase A have been included on page 20 to serve as a reference for level of technology readiness for the missions which are farther out in time.
This document only includes "enabling technologies" for the included missions, that is, technologies/capabilities which are necessary to enable the missions to happen. Other technologies, called "enhancing technologies", which could enable the missions to be more efficient, are not included because we know of no way to bound such lists or get them "vetted".

When missions, or "mission concepts" are in very early stages of development, they are defined by scientists. Engineers enter the picture at a later stage to define the needed spacecraft.. As a result, the lists of enabling technologies included in this document are to areas such as: optics, detectors, thermal, … which are necessary to achieve the desired science.

This document will be updated each time the Origins and SEU Strategic Plans and Roadmaps are updated. It is intended to be used by the Origins and SEU communities, by other organizations with similar technology requirements, and by organizations in the field of technology development. The goal was to be able to list all of the enabling technologies for each of the two Themes on a single page in a manner .

As a service to the reader, this document also includes one-page descriptions of each of the missions for which enabling technology requirements are presented, that is, those missions which are in the Origins and SEU Roadmaps.

System and Component Level Needs

The future technical capability needs that are summarized in this document are a mix of both system and component level requirements. A large telescope aperture is inherently a system of optical surfaces, supporting reaction structure, and probably active controls and wavefront sensors. On the other hand, an energy resolving x-ray detector might be a single chip of superconducting material, a component in a more complex science instrument. The key common characteristic for their inclusion is that each can enable a new astrophysical measurement technique or investigation that is aligned with the long-range goals of the A&P Strategic Plan.

Taxonomy

The technical capabilities that are needed to implement the A&P strategic vision are relatively complex when analyzed in sufficient detail. However, at the top level they can be categorized without excessive loss of fidelity by one of the five technical areas chosen for the Capability Matrix. We recognize that this taxonomy is ultimately imperfect and a few capability needs were placed by management decision rather than pure logic. The definitions used for each category are as follows:

- **Detectors** – Detectors are the transducers that convert the natural electromagnetic carrier of scientific information into electrical signals that can be measured and processed.

- **Optics** – Optics collect, concentrate, manipulate, and analyze electromagnetic radiation and includes the surfaces, precision substrates, and any associated active surface shape controls and wavefront sensors.

- **Thermal** – Cryogenic cooling of detectors and large optical surfaces is required to achieve a key astrophysics benefit of space. It is the ability to minimize the effects of thermal noise by reducing the infrared or heat background radiation of an instrument well below the astrophysical signal of interest as well as to reduce the dark current and therefore increase the sensitivity of the detectors in the instrument. This category contains capabilities for both active and passive cooling of telescope apertures, intermediate optics, and instrument components, particularly detectors.

- **Structures and Metrology –** This category contains the elements of physical, virtual, passive or active structure systems that maintain the precise alignment of optics, detectors and proof masses in order to work as optical instruments and gravitational observatories. Structural control and control sensors/metrology are included in this category.

- **Distributed Spacecraft –** Beyond the size limit of structurally connected systems, distributed spacecraft systems appear to be the means to fully exploit space for extremely high spatial resolution dilute or sparse aperture optical systems. Examples of needed capabilities include precision spacecraft attitude control system components, and micro-thrusters, hyper-precision drag-free capabilities, and efficient multi-spacecraft maneuver algorithms.

Capability Trade-Off Issues - It is possible to find capability requirements within a single mission or related set of missions that appear to be contradictory. These tend to be pairs or groups of needs that impact system performance in a coupled fashion. A few examples include ultra-lightweight optical materials that also have excellent cryogenic thermal conductivity properties and high performance infrared detectors that also have near-room temperature operating conditions. Eventually, system performance must be optimized by tradeoffs between these related capabilities. The goal now is not to resolve the system issues, but to maximize the trade off options that are available. Therefore, we have not attempted to remove the contradictions. Instead, we hope they will lead to creative ideas and better solutions.

ORIGINS		Future				
		Missions in Roadmap			Vision Missions 2015+	
		SAFIR	LIFE FINDER	PLANET IMAGER	Large Aperture UV/Optical Observatory	FIR/Submm Interferometer
Science		study the formation of early stars and galaxies and image planetary system formation in our galaxy	Spectroscopic probe of habitable planets to find evidence of life processes	direct imaging of habitable planets in nearby systems	study large scale structure of the universe, dark matter, baryons, origin and evolution of the elements, formation of galaxies and quasars	study structure development and probe protostars, young planetary systems and debris disks
Architecture		4K cooled 8-10m filled aperture telescope (20-1000um)	FF multi-telescope interferometer (baseline ~100m ?) or smaller (10 to 20 meter) visible coronagraph	FF multi-telescope interferometer (baseline >> 100km)	4-8m primary mirror diffraction limited at 0.5um (4m monolithic to 8m segmented) for wide field imaging & spectroscopy	up to 1Km baseline fizeau interferometer (3x4m apertures)
Wavelength		20-1000um	0.6-28um	0.6-28um	0.1-1um	40-500um
		fir/submm	vis-ir	vis-ir	uv-vis	fir/submm
ENABLING CAPABILITIES	Detectors	Imaging FPA NEP 1E-18 W/Hz^1/2, 10,000 pxls; Spectrosopy array NEP 1E-20 W/Hz^1/2; 1,000 pxls; ~2x2 Coherent receiver array @ near quantum limit	no major issues	Next generation IR FPA (MIR Si IBC, HgCdTe)	(1) >10Kx10K solar blind photon counting array over 0.1-1um (2) energy resolving detector array with R>100 ?	100x100 imaging array with NEP 1e-20 W/Hz^1/2
	Optics	4K, 10m telescope for FIR/submm diffraction limited at 30um and shields to achieve BLIP	Spectroscopic capability. Extreme precision interferometer or Low scattered light large optical aperture	Unprecedented resolution realized with sparse array. Constellation of 100 meter telescopes.	monolithic or segmented with diffraction limit at 0.5um; 1-10Kg/m^2; precision surface optics roughness scalable to needed size. High efficiency optical coatings. Precision deployed and autonomously aligned structure.	4K cooled, 3x4m optics, 1-3 Kg/m^2, 0.5um rms roughness
	Thermal	Thermal engineering & cryocoolers for full optics cooling (4K) & detector cooling (0.1K); thermal uniformity of <1K over aperture, temp stability of <0.1K over TBD?	no major issues	Cryocooler needed for FPA	Cryocooler for energy resolving detector array (100mK)	4K cooled aperture; 100mK cooling for detector
	Distributed Spacecraft	not applicable	Precision FF essential if interferometer is needed	Precision FF essential	not applicable	Precision FF for variable baseline (up to 1Km) interferometer
	Structures & Metrology	Deployable structure in single launch	Precision deployed and autonomously aligned and controlled structure to within optical tolerances.		Precision deployed and autonomously aligned and controlled structure to within optical tolerances.	meters long cryo delay line (beam combining) with full amplitude stroke at 1Hz, 500M cycles)Precision deployed and autonomously aligned and controlled structure to within optical tolerances.

SEU		Future						
		Einstein Probes 2020+			Vision Missions		Cycles of Matter and Energy	
		INFLATION	DARK ENERGY (JDEM)	BLACK HOLE FINDER	BLACK HOLE IMAGER	BIG BANG OBSERVER	ACT	GEN-X
Science		measure gravitational imprint on CMB polarization to probe inflation era	investigate the nature of dark energy	all sky imaging census of accreting black holes	directly image matter falling into black hole at event horizon	direct gravitational probe of inflation era and gravity based probe of blackhole formation and mergers	500eV to 30MeV Advanced Compton Telescope	x-ray imaging of high z galaxies (z=10) to study formation of galaxies and clusters of galaxies
Architecture		<30-40K cooled 4m filled aperture telescope	~2m wide field vis-ir telescope	Coded aperture wide field x-ray telescope	Precision Formation Flying X-ray interferometer	Super LISA system to measure gravity waves	Gamma-ray tracking instrument	Large area grazing incidence x-ray telescope
Wavelength		50-500GHz	0.35-1.7 um	0.002-0.1nm (600-10keV)	0.1-10nm	GRAVITY WAVES	500eV-30MeV	0.1-10nm
		mm	vis-ir	x-ray	x-ray	laser metrology	x-ray, gamma-ray	x-ray
ENABLING CAPABILITIES	Detectors	NEP 1E-18 W/Hz^1/2 10,000 pxl polarimetric array 50-500GHz with multiplexer?(reference newest detector requirements)	~Billion pixel FPA (visible/IR); detector yield (fab) - (350 – 1000 nm) with < 4e- read noise and 0.08 e-/pixel/sec dark current (10.5 um pixels) with > 70% Q.E., - (0.9 – 1.7 um) with < 5e- read noise and 0.02 e-/pixel/sec dark current (18	CdZnTe for hard x-ray (~4-8m^2 area with mm^2 size pixels, ~5mm thick) & low power and scalable asics mux	CCD for x-ray and CdZnTe hard x-ray detector arrays	see structure specs	Track imaging detector event processing using various detectors:Germanium Strip Detectors, Si(Li) Strip Detectors, Xenon Time Projection Chambers, Thin silicon strip detectorsCdZnTe/CdTe	85x85cm^2 detector area probably using CCD technology
	Optics	~4m mirror telescope with high polarization accuracy; polarization modulation	~2m mirror telescope diffraction limited below 1um, large field of view to accommodate large FPA instrument, stable PSF	no major issues	Optically flat (λ/200) 0.5x1.0m mirror arrays ("periscopes"); precision fixturing to < 0.1um and knowledge to 0.5nm	see structure specs	Compton imaging	Low areal density,high resolution, segmented, grazing incidence mirrors; 50m focal length
	Thermal	Cryocooler needed to cool detector arrays (0.1K, lift?); cryosystem to cool aperture to 4K	Passive cooling of FPA to 140K	no major issues	extreme stability ?	heat dissipation management ?	Large capacity cooler needed to operate Ge strip detector at -180C	semi-rigid mirrors must be thermally controlled to minimize thermal movement
	Distributed Spacecraft	not applicable	not applicable	not applicable	Precision formation flying with ~10um precision control over 100km span and 10-100 nasec pointing accuracy	Multiple s/c flying in constellation with large distances (> LISA) with disturbance free proof mass and metrology		6 s/c flying in a loose constellation (6 apertures used to increase collection power)
	Structures & Metrology	lightweight precision structure	lightweight precision structure	lightweight precision structure		Laser metrology with phase noise power spectral density goal of 10^(-8)cycles/sqrt(Hz) @ 0.1 Hz - 100x better than LISA; disturbance free proof mass performance 10x LISA	3500kg (320kg active mass), high precision pointing (30 sec knowledge) required	

PROJECTS IN DEVELOPMENT

ORIGINS		2010	2011	2015	SEU	2010	2014
		SIM	JWST	TPF		LISA	CON-X
Science		uasec astrometry for distance survey and probe nearby stars for earths sized planets	study formation and early evolution of galaxies	study exo-solar planets (formation and development around newly forming stars, search for habitable planets)		probe black hole astrophysics and gravity signatures from big bang	measure velocities and conditions of matter accreting onto black holes
Architecture		10m baseline michelson interferometer (2x35cm apertures) - uasec astrometry	6.5m passively cooled aperture IR telescope	40-60m baseline MIR interferometer or VIS coronagraph ~4mx8m elliptical aperture		3 spacecraft constellation with disturbance free proof masses with sub-nm displacements measured by phase locked lasers	4 1.6m x-ray telescope constellation (not interferometric)
Wavelength		0.5-1um	0.6-28um	0.4-0.9um, 7-17um		GRAVITY WAVES	0.006-5nm (40-0.25keV)
		vis	vis-ir	vis, ir		laser metrology	x-ray
ENABLING CAPABILITIES	**Detectors**	High speed, high sensitivity CCD	NIR 4Mpixel array (NIRCam, NIRSpec), MIR 1Mpixel array (MIRI)	MIR FPA or CCD		Laser: 10yr life, power 1W, freq stability (30Hz/Hz^1/2 at 1mHz), power stability (2E-4/Hz^1/2), phase extraction (<2E-5/Hz^1/2, 1-1000 mHz)	High resolution x-ray calorimeter arrays (1024 elements)
	Optics	sub-nm optical interferometry	high accuracy wavefront sensing and control (inter and intra segment control)	1e10 contrast visible coronagraph or 1e6 contrast IR nulling interferometer		Telescope dimensional stability (~1E-11 at 1 mHz), cumulative wavefront error (~λ/10); pointing stbility (<8E-9 rad/Hz^1/2)	lightweight x-ray optics
	Thermal	thermo-opto-mech modeling & design to ensure mK and pm level accuracy	cryostat plus passive radiator for aperture cooling and instrument cooling (~7K)	cryo delay line		no major issues	Cryocooler needed to cool detectors and other parts of instruments
	Distributed Spacecraft			> 40m baseline multiple s/c interferometer for the formation flying option		**low contamination micro-newton thrusters** (1-100uN) with low thrust noise (<0.1uN/Hz^1/2 in measruement bandwidth)	s/c constellation control
	Structures & Metrology	10m baseline system with nanometer level control of all components & subnm measurement of positions	Deployment from single launch vehicle (folding structure with multi segment aperture)	SIM-like structurally connected interferometer		**disturbance rejection system**: gravitational sensor (residual accel <3E-15 m/s^2/Hz^1/2 at 1E-4 Hz); s/c position uncertainty relative to proof mass (<2.5E-9 m/Hz^1/2); s/c orientation (<1.5E-7 rad/Hz^1/2)	lightweight precision structure

SAFIR

The Single Aperture Far-Infrared Observatory (SAFIR) will combine a large primary mirror with active cooling to provide unprecedented sensitivity at far-IR and submillimeter wavelengths. The observatory will study the formation of structures, from the first stars and galaxies in the distant universe to planetary systems around nearby stars.

Science Goals:

- Probe the epoch of reionization due to the first stars when the universe was less than 1/20 its present age
- Trace the formation and evolution of starforming and active galaxies since their inception.
- Explore the connection between black holes and their host galaxies.
- Reveal the details of star and planet formation in nearby debris-disk systems.
- Search for and quantify prebiotic molecules in the interstellar medium.

Observatory Characteristics:

- Primary Mirror Diameter: 10 m
- Telescope Temperature: 5 K or lower
- Wavelength Coverage: 20 microns to 1 mm

Instruments on board:

- Background-limited detector arrays with thousands of pixels for broad-band imaging over the full wavelength range.
- Moderate resolution (R~1000) spectrometers with background-limited sensitivity and near-unit fractional bandwidth.
- Heterodyne spectrometers tunable over the full wavelength regime with quantum-noise limited performance.

Enabling Capabilities:

- Detectors:
  - Background limited direct detectors for continuum observations from 20-1000 um - 10,000 pixel focal plane array with single pixel sensitivity of NEP 1e-18 W/Hz^1/2
  - Background limited direct detectors for moderate (R<1000) resolution spectroscopy – 1,000 pixel focal plane array with single pixel sensitivity of NEP 1e-20 W/Hz^1/2
  - Heterodyne receivers for high resolution spectroscopy (R up to 100,000) – single channel performance near quantum limit for ν up to 3 THz
- Optics:
  - 10m telescope for FIR/submm diffraction limited at 30um and shields to achieve BLIP
  - ~4K temperature for optics
- Thermal:
  - Thermal management system to control temperature of optics (4K temperature with 1K spatial uniformity over aperture and temperature stability of 0.1K over TBD time), heat shields and other temperature critical components
  - Cryocooler for optics (4K, heat load?) and detector (100mK, heat load?)
- Structures:
  - Structures stability and accuracy to support diffraction limited performance requirement and operational temperature
  - Deployable in single launch

Orbit:

Sun-Earth L2 point, (Alternatives, e.g., a 3 AU orbit, are under consideration.)

Schedule:

Launch > 2020; 5-year mission lifetime

LIFE FINDER

The Life-Finder (LF) will examine a set of exo-Solar System terrestrial planets which have been pre-selected by the Terrestrial Planet Finder (TPF) mission. This pre-selection by TPF will identify planets that have a high probability to harbor evidence of current or past life-processes. The Life Finder mission will examine the submm, infrared and/or the visible spectrum of the reflected and emitted light from each planet to search for evidence of life processes in the atmosphere and on the surface. Information recorded by space telescopes built to observe exo-solar planet occultations (such as Kepler), and theoretical analysis and modeling of planetary evolution will combine with data from TPF, Spitzer, and SAFIR to identify regions of the electromagnetic spectrum most probable for life processes.

Science Goals

- Understand the cycle of life formation and evolution in our solar neighborhood and beyond.
- Understand the physical and chemical interaction between the parent star and the formation of life on planets.
- Understand the role of the evolution of stellar systems on planetary formation

Observatory Characteristics

- Primary Mirror Diameter: ~ 30 meters
- Telescope Temperature: ~140 degrees K
- Wavelength Coverage: 0.6 to 28 microns

Instruments on board

- Coronagraph, baffles,
- Adaptive optics - wavefront sensing & control
- Spectrometer with R~1000 and source-noise limited performance for use in the visible, near infrared
- Background-limited detector arrays optimized for weak signals
- Heterodyne spectrometers tunable over the full wavelength regime with quantum-noise limited performance.

Enabling Capabilities

- Detectors
  - Background limited direct detectors for observations from .6 to 28 um, dynamic range >12-bits
  - Background limited direct detectors for moderate (R<1000) resolution spectroscopy
  - Heterodyne receivers for moderate resolution spectroscopy
- Optical System
  - ~ 30m, diffraction limited at 0.8 micrometer wavelength
  - Wavefront sensing and control at mid and high spatial frequencies
  - Control of unwanted scattered light to <1E-9.
  - Control unwanted thermal radiation
  - Special purpose optical coatings for possible control of polarization
- Thermal
  - Thermal management system to control temperature of heat shields and other temperature critical components
  - Cryocooler needed for focal plane
- Structures
  - Structures stability and accuracy to support diffraction limited performance requirement at the operational temperature
  - Robotically deployed, from a single launch, and autonomously aligned to the limits of the wavefront sensing and control system.

Orbit

- Sun-Earth L2 point, or Sun-Jupiter L2 point

Schedule:

- Launch > 2020; 10-year mission lifetime -

PLANET IMAGER (PI)

The Planet Imager will be a telescope system to image an exo-solar planet with a spatial resolution sufficient to directly image habitable planets in near-by systems.

Science Goals:

Underdevelopment - examples given here.

- Examine large scale spatial features on the surface of an exo-solar planet to understand :
- Geologic activity
- Surface characteristics (solid, liquid, vegetation, etc.)
- Gravitational interaction with satellites
- Electromagnetic fields and the presence of a magnetic field on the surface
- Atmospheric clouds
- Energy transport

System Characteristics:

- Free flying multi-telescope interferometer at 100km to 1,000km baseline (aperture) with a fill-factor of >10% (is this correct? For a linear array, 100km with 10% fill implies filling 10km of baseline by a combination of real aperture and s/c movement; for 2 dimensional array, it is far worse), and diffraction limited in the visible, with an effective focal length of 12 to 120 km.

Enabling Capabilities (in planning)

- Detectors:
  - Background limited direct detectors for observations from .6 to 28 um, dynamic range >12-bits
  - Background limited direct detectors for moderate (R<1000) resolution spectroscopy
  - Heterodyne receivers for moderate resolution spectroscopy
- Optics:
  - A constellation of >100meter clear aperture telescopes with a free-flying instrument package and focal planes.
  - Wavefront sensing and control
  - Beam recombination methodologies
- Thermal:
  - Thermal management system to control temperature of heat shields and other temperature critical components
  - Cryocooler needed for focal plane
- Structures:
  - Structures stability and accuracy to support diffraction limited performance requirement at the operational temperature
  - Robotically deployed and aligned to the limits of the wavefront sensing and control system.
- Precision formation flying:
  - Precision control a constellation of hundreds of 100 meter diameter telescopes.

Orbit:

- Sun-Earth L2 point or outside the solar system

Schedule:

- Launch > 2050; > 20-year mission lifetime

LARGE APERTURE UV OPTICAL OBSERVATORY

The Large Aperture UV Optical Observatory is a 4 to 8 meter diffraction-limited optical system with imaging, spectral and polarization measurement capability across the ultraviolet region of the spectrum to observe large-scale structure of the universe, dark matter, baryons, the origin and evolution of the formation of the elements, galaxies and quasars. The Hubble Space Telescope science shows a wealth of information critically important to our understanding of the Origins of man in the Universe in the high-spatial resolution ultra-violet region of the spectrum. The JWST will not record data in a very important spatial-spectral region of the Universe below 0.6um, and therefore this telescope will full fill an important cornerstone to our understanding answers to the questions: Are we alone? How did we get here?

Science Goals:

- Understand how stars and galaxies were formed out of the primordial matter in the universe
- Understand the evolution of young Galaxies and the distribution of the elements
- Large scale structure and dark matter
- Protostars and stellar jets

Observatory Characteristics:

- Primary Mirror Diameter: 4 to 8 meters
- Optics precision fabricated and coatings optimized for ultra-violet
- Wavelength Coverage: 0.1 to 1.0 micrometers

Instruments on board: "in planning":

- High resolution imaging spectrometer (R~10,000)
- Polarization analysis with a medium resolution (R~1000) imaging spectrometer
- Ultra-low light-level wide-field imager
- Coronagraph, baffles, masks

Enabling Capabilities: "in planning"

- Detectors:
  - >10Kx10K solar blind photon counting array over 0.1-1um
  - Photon counting and energy selective detectors with R~100
- Optical System:
  - 4 to 8 meter diffraction limited at 0.1 micron super smooth mirror
  - Wavefront sensing and control
  - Control unwanted thermal radiation
  - Special purpose optical coatings
- Thermal:
  - Cryocooler needed for photon counting and energy selective detectors
- Structures:
  - Structures stability and accuracy to support diffraction limited performance requirement at the operational temperature
  - Robotically deployed, from a single launch, and autonomously aligned and controlled to initialize and sustain diffraction limited performance at 0.1-micron wavelength.
  - < .1 milli arc second control and pointing

Orbit:

- Sun-Earth L2 point, or Sun-Jupiter L2 point

Schedule:

- Launch > 2015; 10-year mission lifetime

FAR-INFRARED AND SUBMILLIMETER INTERFEROMETER

The Far-Infrared and Submillimeter Interferometer will be a high resolution Fizeau-interferometer imaging system with angular resolution of 20 milliarc-seconds at a wavelength of 100 micrometers to study the physical conditions within young collapsing protostars deeply imbedded in their parental molecular clouds and to study galaxies that are highly obscured by their " dust of formation". The system will observe the formation of proto-planetary systems

Science Goals: - "in planning"

- Understand the evolution and structure formation in young planetary systems and debris disks.
- Study the physical conditions within young collapsing protostars deeply imbedded in their parental molecular clouds

System Characteristics: - "in planning"

- Free flying precision-controlled multi-telescope interferometer at 1km to 5km baseline (aperture)
- Three 15 to 25 meter telescopes.

Enabling Capabilities: - "in planning"

- Detectors:
  - Background limited direct detectors for observations from 40 to 500 um
  - Background limited direct detectors for moderate (R<1000) resolution spectroscopy
  - Heterodyne receivers for moderate resolution spectroscopy
  - Large area direct and heterodyne receivers.
- Optics:
  - Advanced wavefront sensing and control
  - Low emissivity coatings and baffles
  - Innovative control of unwanted thermal background radiation
- Thermal:
  - Thermal management system to control temperature of heat shields and other temperature critical components
  - Cryocooler needed for focal plane
- Structures:
  - Structures stability and accuracy to support diffraction limited performance requirement at the operational temperature
  - Robotically deployed, and autonomously aligned.
- Precision formation flying:
  - Control a constellation of hundreds of 100-meter diameter telescopes.

Orbit

- Sun-Earth L2 point or outside the solar system

Schedule

- Launch > 2050 with > 20-year mission lifetime

LISA (Laser Interferometer Space Antenna)

As the first dedicated space-based gravitational wave observatory, LISA will detect waves generated by binaries within our Galaxy (the Milky Way) and by massive black holes in distant galaxies. LISA will use an advanced system of laser interferometry for detecting and measuring them, *directly* detecting the existence of gravitational waves, rather than inferring it from the motion of celestial bodies, as has been done previously.

Science Goals:

- To detect gravitational waves from sources involving galactic (within the Milky Way) binaries and extra-galactic (outside our Galaxy) massive black holes.

System Characteristics:

- ORBIT: 20 degrees behind Earth's orbit of the Sun, at 1 AU (astronomical unit) from the Sun, with the plane of orbit inclined at 60 degrees to the ecliptic.
- SPACECRAFT MASS: Each spacecraft has a mass of 203 kilograms (447.5 pounds). Each propulsion unit weighs 132 kilograms (291 pounds) and requires 27 kilogram (59.5 pounds) of propellent. Total launch mass is 1407 kilograms (3102 pounds).
- INSTRUMENT: identical in each of LISA's three spacecraft ——30 centimeter (almost 12 inches) diameter f/1 Cassegrain telescope

Enabling Capabilities:

The Disturbance Reduction System (DRS):

- Gravitational sensor performance: low residual acceleration, relative position sensing, proof mass control, charge control. residual acceleration ($<3x10^{-15}$ m/s^2/√Hz, at 10^{-4} Hz), relative position sensing ($<1x10^{-9}$ m/√Hz, over the MBW). Current TRL is ~3.
- Thruster system: micro-newton thrust, thrust noise, lifetime, contamination. : thrust (1-100 µN), thrust noise (<0.1 µN/√Hz in the measurement bandwidth, MBW), lifetime (10 yr), contamination (TBD). Current TRL of Centrospazio cesium FEEP thruster is 4.
- Control laws: multiple degree-of-freedom control strategy, stability, robustness. spacecraft position relative to proof mass ($<2.5x10^{-9}$ m/√Hz, over the MBW), spacecraft orientation ($<1.5x10^{-7}$ rad/√Hz, over the MBW). TRL set by the gravitational sensor.

Laser Interferometer:

- Laser: power, frequency noise, amplitude noise, lifetime. Laser: power (1 W), frequency stability (30 Hz/√Hz at 1 mHz), power stability ($2x10^{-4}$ /√Hz at 1 mHz), lifetime (10 yr). Current TRL is 4-8, depending on supplier and design.
- Laser frequency control: frequency stabilization, frequency reference, offset-locking, Laser frequency control: absolute frequency reference (~10 MHz), phase noise ($<2x10^{-5}$ cycles/√Hz, .001 to 1 Hz). Current TRL is 3.
- Optical system: dimensional stability of telescope, flight qualified components and assemblies, cumulative wavefront error. Optical system: dimensional stability of telescope ($\sim1x10^{-11}$ at 1 mHz), cumulative wavefront error ($\sim\lambda/10$). TRL is ~3.
- Phase measurement system: phase extraction, clock and laser frequency noise correction. Phase extraction ($<2x10^{-5}$ cycles/√Hz, .001 to 1 Hz), laser frequency noise correction ($\sim10^{-8}$), clock frequency noise correction ($\sim10^{-3}$). TRL is ~3.5, based on GRACE receiver.
- Beam pointing: pointing sensor, pointing actuator, pointing stability. Beam pointing: pointing stability ($<8x10^{-9}$ rad/√Hz, in MBW). TRL has not been determined.

CON-X
Five year mission to perform high throughput X-ray spectroscopy to unlock the mysteries of black holes, galaxy formation, and dark matter

Science Goals
1. Measure the X-ray spectra of the faintest sources in the Roentgen Satellite (ROSAT) Deep Surveys and the Chandra deep fields in less than 10^5 seconds. 2 Test General Relativity in the strong gravity limit by mapping the inner emission regions of black holes. 3. Search for the “dark matter” or “missing baryons” from observations of the Intergalactic Medium (IGM). 4. Study the interchange of matter and energy between stars and the Interstellar Medium (ISM), and the enrichment of the IGM and Intracluster Medium (ICM) and the evolution of clusters of galaxies.

System Characteristics
Four identical X-ray telescopes in L2 orbit. One Spectroscopy X-ray Telescope and 3 Hard X-ray Telescopes per spacecraft; each with 10 meter focal length

Enabling Capabilities
X-ray mirror with the required angular resolution given weight and size constraints. Fom the top level flux sensitivity and spectral resolution requirement (in conjunction with grating dispersion), the Half-Power Diameter (HPD) of the entire telescope must be smaller than 15 arc seconds. The SXT mirror must provide an HPD better than 10 arc seconds.

Orbit
L2

INFLATION PROBE (CMB POL)

The Inflation Probe will map the polarization structure of the Cosmic Microwave Background (CMB). The probe will be designed to detect the signature of the gravity waves produced by an inflationary expansion just ~10^{-38} seconds after the Big Bang. Detection of the signature of this inflationary gravity-wave background (IGB) in the polarization of the CMB would provide a direct probe of physics at the highest energies and earliest times of any experiment yet conceived.

Science Goals:

- Definitively search for the IGB polarization signal, with sensitivity limited by astrophysical foregrounds.
- Use polarization produced by gravitational lensing to probe the linear matter power spectrum.
- Map the polarization of the CMB sky to the limit set by cosmic variance of the grad-mode CMB signal into the damping tail.

System Characteristics:

- Primary Mirror Diameter: 2-4 m, cooled to 30-50 K
- Polarimetric imaging with wide field of view (100 deg^2), diffraction limited at 500GHz and low polarization
- Large-format arrays with ~10^4 elements (TES/SQUID bolometers, MKID, or HEMT array receivers)
- Frequency Coverage: 30 to 500 GHz

Enabling Capabilities:

- Detectors:
  - Direct detector FPA with NEP ~ 1e-18 W/Hz^1/2 over 30-500GHz & 10^4 elements
  - HEMT receiver array with Q/U polarimetric instrumentation with sensitivity at quantum limit
- Optics:
  - 2-4 m telescope primary telescope, passively or actively cooled to 30-50 K.
  - Low polarization
  - Active polarization modulator for noise stabilization, improve Q/U sampling
  - Large optical throughput (diffraction limited at 500GHz and 100 deg^2 FOV)
  - May require broad-band refracting elements to achieve throughput (e.g. waveplate, lens)
- Thermal:
  - Active or passive cooling system for telescope to 30 – 50 K.
  - Intermediate cooler to 4 K (may be active ACDTP cooler or liquid helium).
  - Cryocooler for focal plane to 100 mK operating from 4 K base temperature with 5 uW heat lift.
  - Thermal management system to control temperature of telescope, 4 K optics, and 100 mK focal plane to required stability
- Structures:
  - Structures stability and accuracy to support diffraction limited performance requirement and operational temperature

Orbit:

- Sun-Earth L2 point

Schedule:

- Launch > 2010, as described in NRA-03-OSS; > 1-year mission lifetime to allow redundant mapping of entire sky.

DARK ENERGY PROBE - JDEM (Joint Dark Energy Mission)

The Joint Dark Energy Mission (JDEM) is the result of a joint NASA – DOE agreement to investigate the nature of the Dark Energy, the mysterious component that makes up approximately 70% of the energy density of the Universe. A joint NASA/DOE AO will solicit a Dark Energy investigation requiring a spaced-based observatory and an appropriate focal plane. Because the investigation will be competed, it is not possible to be specific about the instrument requirements at this stage. Outlined below is a generic description of what the mission is likely to look like.

Science Goals:

- Precisely determine the fraction of the Universe's energy density contained in the Dark Energy.
- Measure the pressure/density ratio (the *equation of state*) of the Dark Energy.
- Constrain the variation in the equation of state with redshift.
- Distinguish among competing theories for the dynamical evolution of Dark Energy.
- Use Type Ia Supernovae to measure the expansion history of the Universe

System Characteristics:

- Primary Mirror Diameter: ~ 2 m
- Telescope Temperature: 300 K
- Wavelength Coverage: visible / near-IR

Instruments on board:

- Massive focal plane array covering the visible and near-IR to perform a survey to discover supernovae Ia, perform a galaxy weak lensing survey, and perform other astronomical surveys. Precise photometric calibration is required.
- Moderate resolution spectrometer (visible / near-IR) to precisely characterize the cataloged supernovae near peak brightness.

Key Technologies:

- Detectors:
  - Focal plane will be very large: detector yield is a critical issue.
  - Visible detectors (350 – 1000 nm) with < 4e^- read noise and 0.08 e^-/pixel/sec dark current (10.5 µm pixels) with > 70% Q.E.
  - Near-IR detectors (0.9 – 1.7 µm) with < 5e^- read noise and 0.02 e^-/pixel/sec dark current (18 µm pixels) with > 65% Q.E.

- Optics:
  - 2m telescope diffraction limited below 1 µm
  - Extremely wide field to accommodate very large focal plane
  - highly stable PSF required

- Thermal:
  - Thermal management system to control temperature of room temperature optics
  - Passive cooling of focal plane to ~ 140 K

Orbit:

- Sun-Earth L2 point (alternative is highly eccentric 3 day orbit)

Schedule:

- Launch ~ 2013; 5-year mission lifetime

ACT (Advanced Compton Telescope)
Compton telescope with improvements in solid state detector technologies to provide the necessary energy and spatial resolution as well as background reduction.

Science Goals
• Direct observations of their radioactive debris, and similar studies of core-collapse supernovae.
• Mapping the Galaxy in a broad range of nuclear line emissions
• Observation of the gamma rays from matter accretion onto galactic compact objects and massive black holes in AGN.
• Use polarization to determine the emission processes in gamma ray bursts, pulsars and AGN
• Clarify the origins of multiple components of the diffuse cosmic gamma ray background

Enabling Capabilities:

System Characteristics
The new technology that all the ACT instrument concepts share and depend on is "gamma-ray tracking." This is an entirely new field, opened up for the first time by the powerful new detector technologies that are now available. Tracking is the science of stringing together each of the individual interactions that a gamma ray undergoes in the proper order, based solely on the energy loss and positions of these interactions.

Track imaging detector event processing:

> The development of computer tools to accurately simulate, and process, and analyze 3-dimentional gamma-ray tracking detector data is lagging somewhat behind the detector development. Improvements are needed in the Monte Carlo simulation of medium- and high-energy photon interactions. Specifically, improvements are needed in the momentum and energy distributions, including polarization effects, of the recoil electron from Compton scattering and the electron and positron from pair production.

Other enabling technologies of lower priority are as follows:
- Front-end electronics development: primarily an engineering issue
- Cooling technology: Cooling technology for a large 3-dim solid state detector will require new innovative designs.
- Cost and Cost reduction: large volume of the detector needed to achieve the required ACT. Sensitivity makes this an expensive detector

Orbit
Low inclination LEO

GEN-X

X-ray observatory with an effective area of 150 m ^2 at 1 keV and an angular resolution of ~ 0.1 arc second. It will be able to image 1000 times deeper than Chandra , observing sources with a flux of 2 x 10 -20 ergs/cm 2/s. It will also be able to obtain high resolution spectra from sources 100-1000 times fainter than those observable by Constellation-X .

Science Goals

The primary science objectives of the Generation-X mission are: (1) to study the early universe where galaxies and black holes were forming and growing rapidly; (2) to study the chemical evolution of the universe as to where the metals are formed and how they are spread to where they are; (3) to study the formation and evolution of massive black holes in the local universe; and (4) to study the formation and evolution of stellar-mass black holes in nearby galaxies.

System Characteristics

6 identical spacecraft, each with 25 meter grazing incident x-ray telescopes in an L2 orbit. The figure of the mirrors is comparable to that of the Chandra mirrors; its axial figure error should be of the order of 0.1 or better. Given weight limitations, mirrors will be only as thick as 0.15 to 0.3 mm which is a factor of 100 thinner than those of Chandra.

Enabling Capabilities

Manufacturable low areal density mirrors:
(1) figure quality: half-power diameter (HPD) of two reflections be less than or comparable to 1 second.
(2) mass per unit mirror area, or areal density, should be less than or comparable to 0.5 kg/m^2.
(3) Manufacturing and alignment cost and speed: they should be such that the development of Generation-X can be accommodated in a normal phase C/D development program of 5 years.

Orbit

L2

BLACK HOLE FINDER

The Black Hole Finder Probe will perform an all-sky imaging census of accreting black holes, from supermassive black holes in the nuclei of galaxies, to stellar mass black holes in our Galaxy.

Science Goals

The Black Hole Finder Probe will survey the local Universe over a wide range of black hole obscuration and accretion rates to identify the most luminous obscured black holes at larger redshifts in order to estimate the growth rate of massive black holes; and discover ordinary stars being torn apart as they approach black holes.

System Characteristics

Three identical hard X-ray coded aperture imaging telescopes viewing contiguous potions of the sky on one spacecraft.

Enabling Capabilities

- large area (4-8m^2) , low-cost (~$200/cm^2), high-uniformity CZT
- tiled ASICs (large scale) with 50-75 mW per pixel (<600W, total)
- digital bus architecture to read all the ASICs and combine the data; high data volume and need for on-board processing for rapid GRB (10sec) and transients (1 orbit) positions
- coded aperture imaging with curved (or faceted) masks; scanning geometry

Orbit

LEO

BIG BANG OBSERVER
Gravity wave experiment with spacecraft separation of 50,000 km

Science Goals
Direct detection of gravitational waves, perhaps at periods of 0.1-10 sec. In this frequency range, the primary source of foreground signals is expected to be neutron star binaries several months before coalescence, and these are few enough that they can be identified and removed. Measurement of these merger signals will also directly determine the rate of expansion of the Universe as a function of time, extending the results of the Dark Energy Probe

System Characteristics
Multiple identical heliocentric s/c for gravity wave measurement

Enabling Capabilities
- BBO strain noise goal is 1000 x better than LISA
- Because baseline is 100x shorter, interferometer displacement sensitivity is 100,000x better than LISA
- Observation frequency of 0.1 Hz vs 1 mHz for LISA eases some requirements
- BBO acceleration noise goal is 10x better than LISA
- BBO goal at 0.1 Hz may be demonstrated by ST7/SMART2 or by LISA

Orbit
Heliocentric

BLACK HOLE IMAGER
X-ray interferometer

Science Goals
The principal science requirement is to resolve the event horizons of black holes and study matter in the extreme gravitational limit.

System Characteristics