Chapter 3. Technology Roadmap: Beyond Einstein

The *Beyond Einstein* program cannot succeed without investment in key enabling technologies for each mission. No mission can go into full flight development before it has achieved the appropriate level of technical readiness. This requires a well-balanced technology program, in which both near- and long-term mission needs are addressed. Technology development for *Beyond Einstein* must be coordinated with other Space Science themes to identify cost sharing opportunities. Technology from early missions must be extended for later, more demanding missions. Scientists, the end-users of the technology, must be involved at all stages to ensure that mission requirements are met.

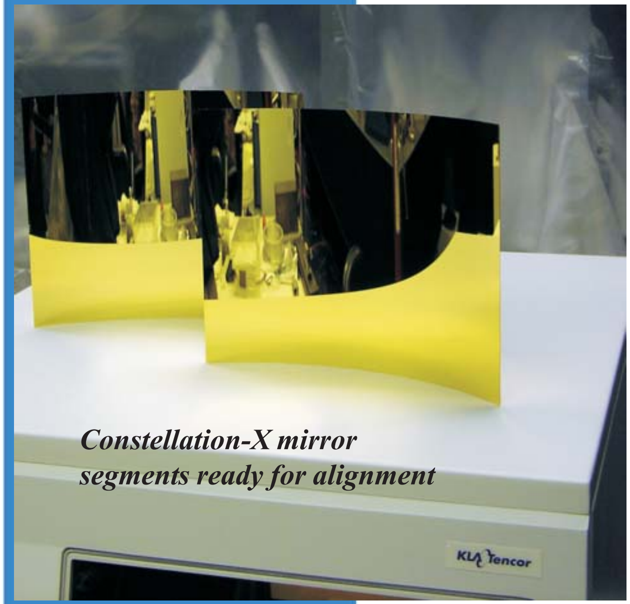
> *"On a long trek, your eyes arrive first. Your feet arrive last."*
> —*African Proverb*

Einstein Great Observatory Technologies

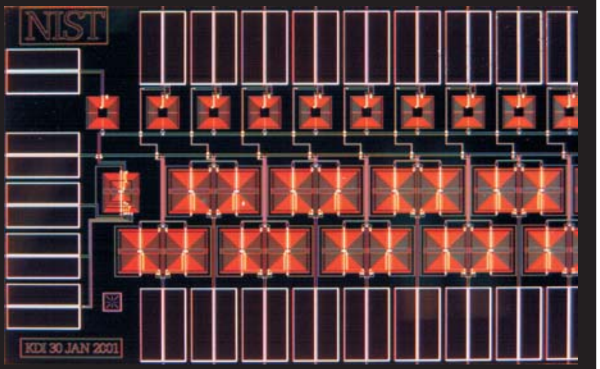
Both Einstein Great Observatory missions have been under study for several years and have detailed technology roadmaps in place. We highlight key elements below:

Constellation-X

Constellation-X will provide X-ray spectral imaging of unprecedented sensitivity to determine the fate of matter as it falls into black holes, and map hot gas and dark matter to determine how the Universe evolved large-scale structures.



Constellation-X mirror segments ready for alignment



SQUID multiplex chip used for reading out TES microcalorimeter arrays. NIST/Boulder.

Lightweight, grazing incidence X-ray optics. Each of the four identical Constellation-X spacecraft will carry two sets of telescopes: (1) a spectroscopy X-ray telescope (SXT) for the low energy band up to 10 keV, and (2) three hard X-ray telescopes (HXTs) for the high energy band. Both incorporate highly nested, grazing-incidence X-ray mirror arrays, which must simultaneously meet tight angular resolution, effective area, and mass constraints. Engineering test units of both SXT and HXT mirrors are under development: glass substrates with surfaces replicated from precision mandrels for SXT and HXT, and an alternative replicated nickel shell design for HXT.

X-ray calorimeter arrays. Two technologies are being developed in parallel: semiconducting bolometers and voltage-biased transition-edge superconducting thermistors. Both have made substantial progress toward the required energy resolution of 2 eV. Multiple approaches to fabrication of high-quality arrays and multiplexed readout amplifiers are under development.

Long-lived 50mK coolers. Constellation-X requires reliable long-life first stage coolers operating at 5–10 K. The Advanced Cryocooler Technology Development Program (ACTDP) is already pursuing this goal through study-phase contracts, leading to completion of two demonstration coolers in 2005. The ultimate detector temperature of 50 mK will be reached by one of several adiabatic demagnetization refrigerator technologies currently under study.

Grazing incidence reflection gratings. Reflection gratings dispersed onto CCDs provide imaging spectroscopy in the 0.2–1.5 keV energy range and are similar to those flown on XMM-Newton. For Constellation-X, improvements to reduce weight and in-

A prototype mirror segment for Constellation-X being separated from the replication mandrel.

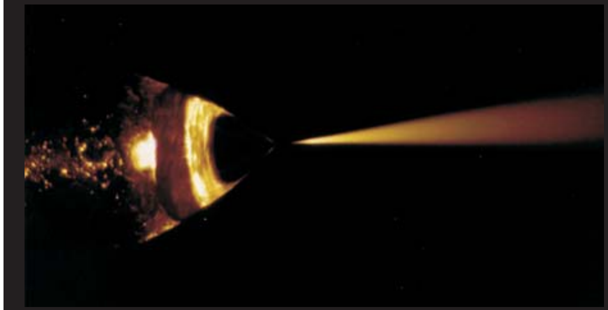
crease resolution are under study. Novel event-driven CCDs have recently been developed that provide significant improvements in performance and robustness.

Solid-state hard X-ray imaging detectors. At hard X-ray energies, CdZnTe detectors provide < 1.2 keV resolution and high quantum efficiency over the 6–50 keV energy range. Key requirements have been demonstrated but work is continuing on extending the response at low energies and reducing the effects of electron trapping.

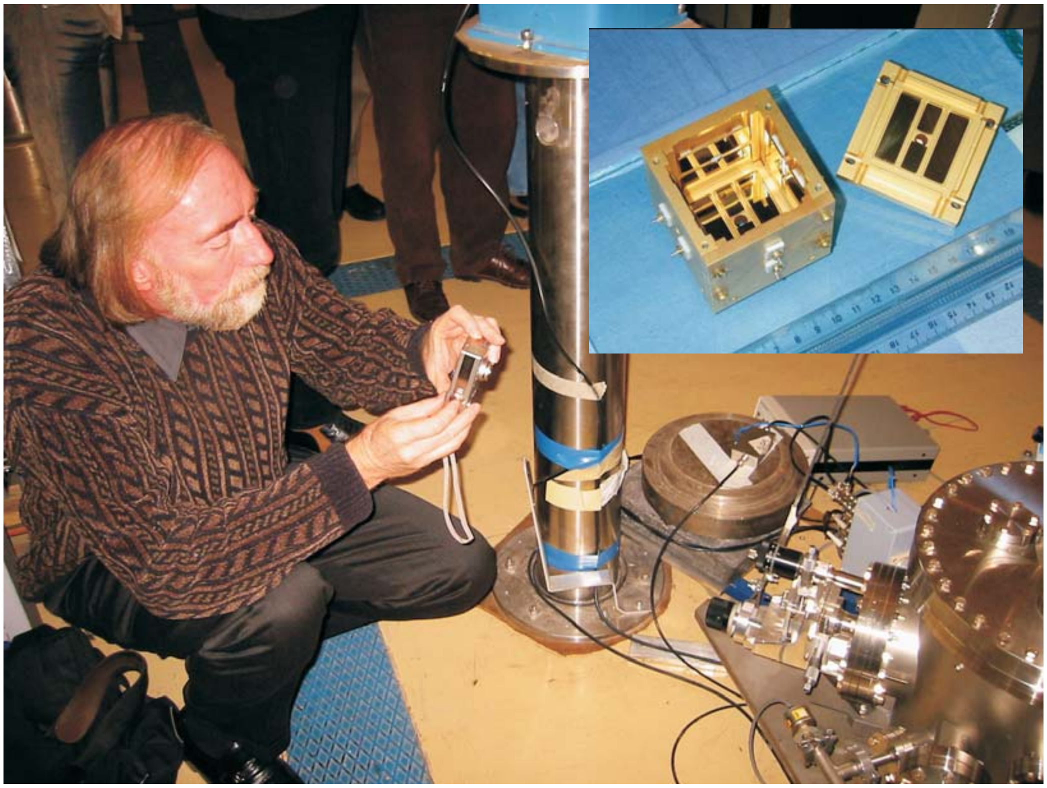
LISA

LISA will open a new window on the Universe by enabling the detection of gravitational radiation from a wide variety of astronomical systems. It consists of a triangle of reference masses in solar orbit connected by a precision metrology system. The measurement of the relative motion of these drag-free masses allows us to sense the passage of gravitational waves through the Solar System. To use the capture of compact objects to map spacetime outside of supermassive black holes sets the sensitivity requirements at wave frequencies of 10^{-2}–10^{-3} Hz. To measure the properties of merging pairs of supermassive black holes requires good sensitivity down at least to 10^{-4} Hz.

The key technologies are those to (1) minimize external disturbances of the reference masses, and (2) precisely measure their separation.



A micronewton thruster test firing, a technology required for the LISA mission.



Gravitational reference units of the kind shown (inset) and here undergoing testing are at the heart of the LISA mission.

Disturbance Reduction System. Micronewton thrusters keep the spacecraft precisely centered about the masses. Several types which meet LISA's noise requirements have been demonstrated, and lifetime and space testing are planned. Correction signals are sent to the thrusters by gravitational reference units (GRUs), which also serve as the reference mirrors for the laser measurement system. Improvements in existing GRUs (such as those flying on the NASA/German GRACE mission) that will extend LISA's sensitivity below 10^{-3} Hz are under development.

Laser Measurement System. LISA's sensitivity above 10^{-3} Hz is set by the laser power and the measurement system. Changes in the 5×10^6 km test mass spacing must be measured to 10^{-11} m, or 10^{-5} fringes. That requirement can be met by existing lasers and detection systems. But orbital dynamics lead to changes in spacecraft spacing that can create a fringe rate as large as 15 MHz. This imposes stringent requirements on laser frequency stability, telescope pointing and dimensional stability, and the phase measurement system, including ultra-stable oscillators.

System Verification. A validation flight is planned in June 2006 on the ESA SMART-2 spacecraft, with US participation through the New Millennium mission ST-7. This program will be an important validation of the critical disturbance reduction system components, the gravitational reference units, micronewton thrusters, and the laser interferometer to measure test mass spacing.

Technology Development for the Einstein Probes

The Einstein Probe mission concepts will be competed in order to choose the best scientific and technical approaches to their goals. All of the measurements planned for the three Einstein probe missions are technically challenging. Readiness must be evaluated before each competition. This will require an Einstein Probe technology development

Einstein's general theory of relativity has a practical application which affects many people in their work and play. The U.S. Global Positioning System, or GPS, used by the military and civilians for navigation and other purposes, includes corrections for the effects predicted by relativity. A portable GPS receiver determines position by simultaneously receiving signals from atomic clocks on the GPS satellites. If relativity were not accounted for, the clocks on-board each satellite would run faster than clocks on the ground by about 38 microseconds per day. This may sound small, but the GPS system requires accuracy ten thousand times higher than this. If relativity were not taken into account, a navigational fix based on the GPS constellation would be false within minutes, and errors in positions would accumulate at a rate of about 10 kilometers each day. The whole system would be utterly worthless for navigation!

program. This program should be provided as early as possible to allow all of the promising approaches to each mission to be thoroughly vetted.

Some particular mission concepts are already being studied for each of the Probe science areas. Below we discuss the technology development required for these candidate concepts.

Dark Energy Probe

The Dark Energy Probe will be designed to perform measurements of the geometry of the Universe in the redshift range $z = 0.7–1.7$, where the effects of dark energy are expected to leave their most prominent signature. A particularly promising approach (and the one emphasized in the NAS CPU report) is to obtain a large sample of Type 1a supernovae to redshifts of at least $z = 1.5$.

A mission capable of such observations requires a wide field of view telescope with about a 2-meter diameter mirror, diffraction limited down to 1 micron, and large arrays of optical and infrared imaging detectors. All of these elements require substantial technology development. The primary mirror must have much lower cost and mass-per-unit-area and be developed faster than the HST primary. The very large detector arrays are a serious challenge: they require of order a billion pixels. At optical wavelengths, silicon-based CCDs are the obvious candidates, but the requirements exceed the capabilities of current devices. At infrared wavelengths, the gap between requirements and current devices is even larger.

Inflation Probe

The Inflation Probe aims to detect signatures of gravitational waves (with wavelengths comparable to the size of the Universe) produced by quantum fluctuations of spacetime during inflation. It will do this by measuring the weak imprint they leave on the polarization of the cosmic microwave background.

Even for optimistic models, however, this weak polarization component is very difficult to detect. It is an order of magnitude weaker than the polarization components produced by quantum fluctuations in the inflation field. The sensitivity required is roughly 20–100 times that of the HFI focal plane detector on *Planck*. Achieving such a vast increase in sensitivity requires significant advances: e.g., large arrays of polarization-sensitive detectors with frequency multiplexing from 50–500 GHz. Other technical challenges include the need for cold optics at low cost and 100 mK detector operating temperatures with very stable temperature control.

Black Hole Finder Probe

The Black Hole Finder Probe will conduct a wide field survey of black holes. It is likely to operate at hard X-ray/soft gamma-ray energies, where radiation emitted from these objects can penetrate any surrounding veil of gas and dust.

Such a survey instrument would need to be sensitive over an energy range of about 10–600 keV, and to have angular resolution less than 5 arcmin. Since reflective optics provide very limited fields of view at these high energies, the telescope must use coded aperture imaging. To provide sufficient sensitivity, the detector plane must have an area of several square meters with millimeter-sized pixels to provide the required angular resolution. A CdZnTe detector array seems the most likely candidate, but there remain technical challenges. Other technology problems arise in the areas of mask fabrication and data acquisition at high trigger rates.

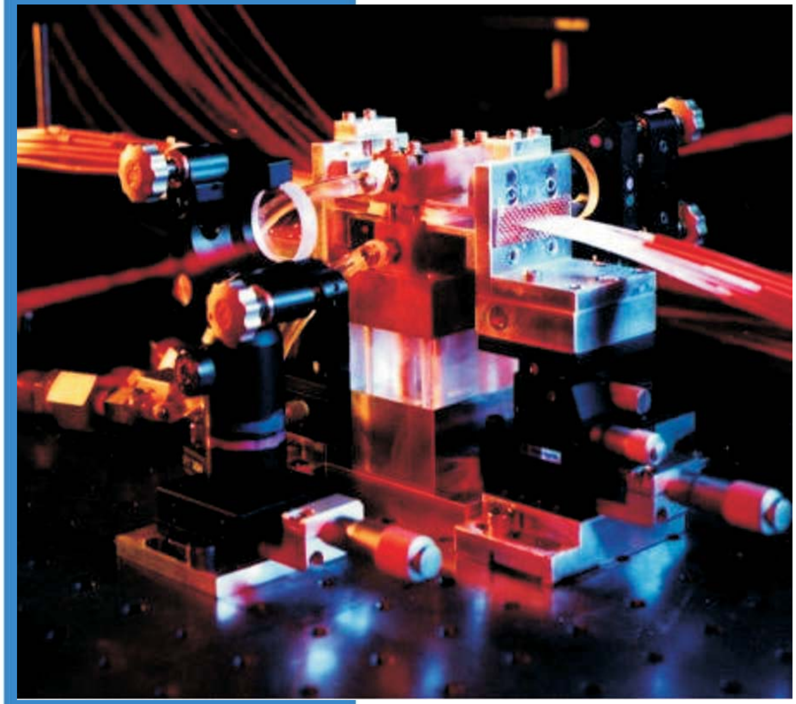
Technologies for Beyond Einstein Vision Missions

The ultimate visions of the *Beyond Einstein* program stretch well beyond what will be accomplished with either the Einstein Great Observatories or the Einstein Probes. Although detailed designs for successor missions would be premature, it is important to begin addressing some of the anticipated technology needs.

Big Bang Observer

The ultimate goal of a Big Bang Observer is to directly observe gravitational waves with sufficient sensitivity to observe the background due to the quantum fluctuations during inflation. This must be accomplished in the face of a strong foreground of gravitational waves produced by all the binary stars and black holes in the Universe. Source-by-source removal of this foreground is practical at wave periods of 0.1–10 seconds.

To separate these foreground sources requires extraordinary sensitivity and angular resolution. One possible solution consists of four separate interferometers, each including three spacecraft separated by 50,000 km. These would be spaced in a triangle around the earth's orbit about the Sun (separations



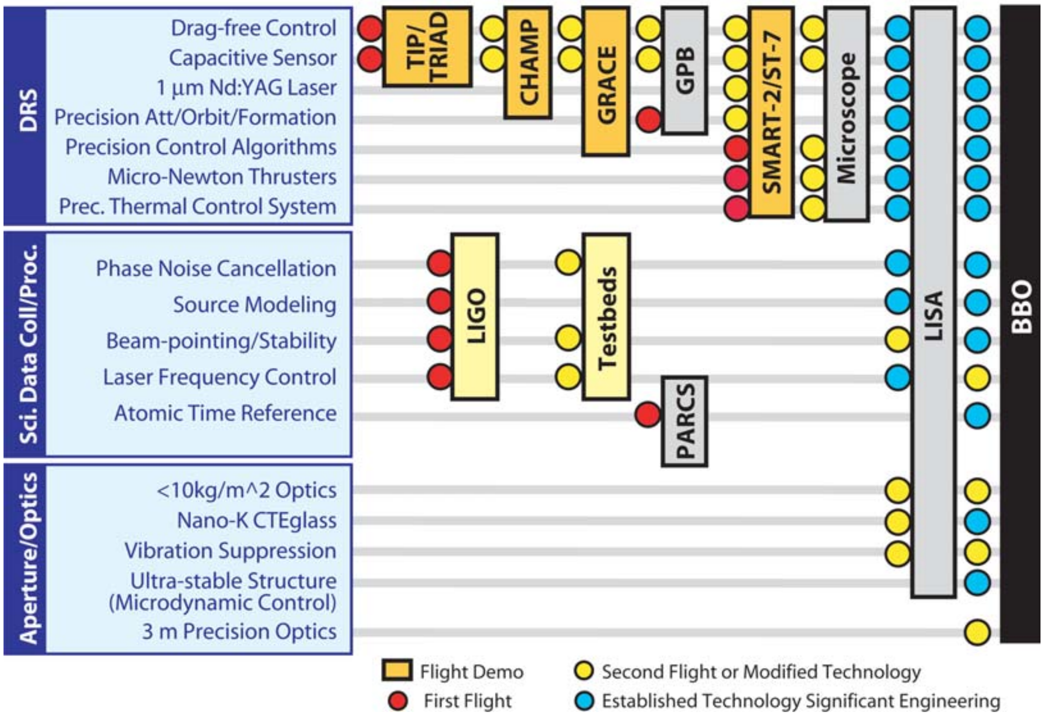
The Big Bang Observer will require powerful space-qualified lasers. Here a 125 W laser (scalable to 30 kW) is shown under test.

laser interferometer space antenna

constellation-x

einstein probes

Strategic Technology Infusion Flow - Gravitational Wave Missions



of 1.7 times the Earth-Sun distance), with two interferometers sharing one apex for independent correlation. Such a configuration imposes many technical challenges, including:

Strain Sensitivity. A significant improvement in strain sensitivity, about 10,000 times better than that of LISA is needed. This will require advances in mirror fabrication, laser power and stability, phase measurement, and instrument pointing.

Acceleration Noise. A gravitational reference sensor with acceleration noise performance 100 times lower than that planned for LISA is required.

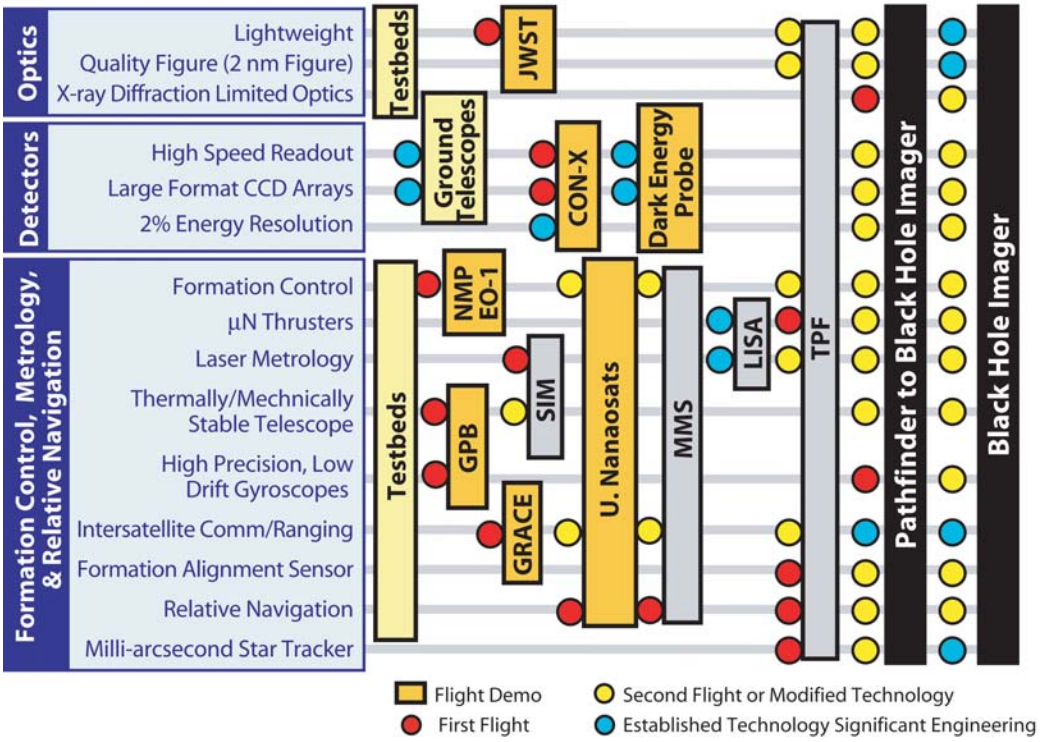
This gravitational wave frequency band will not have been previously explored. To provide scientific guidance and to reduce the risk associated with making such large technical advances in one step, it would be desirable to first fly a pathfinder mission with fewer spacecraft and more modest improvements on LISA's technology.

Black Hole Imager

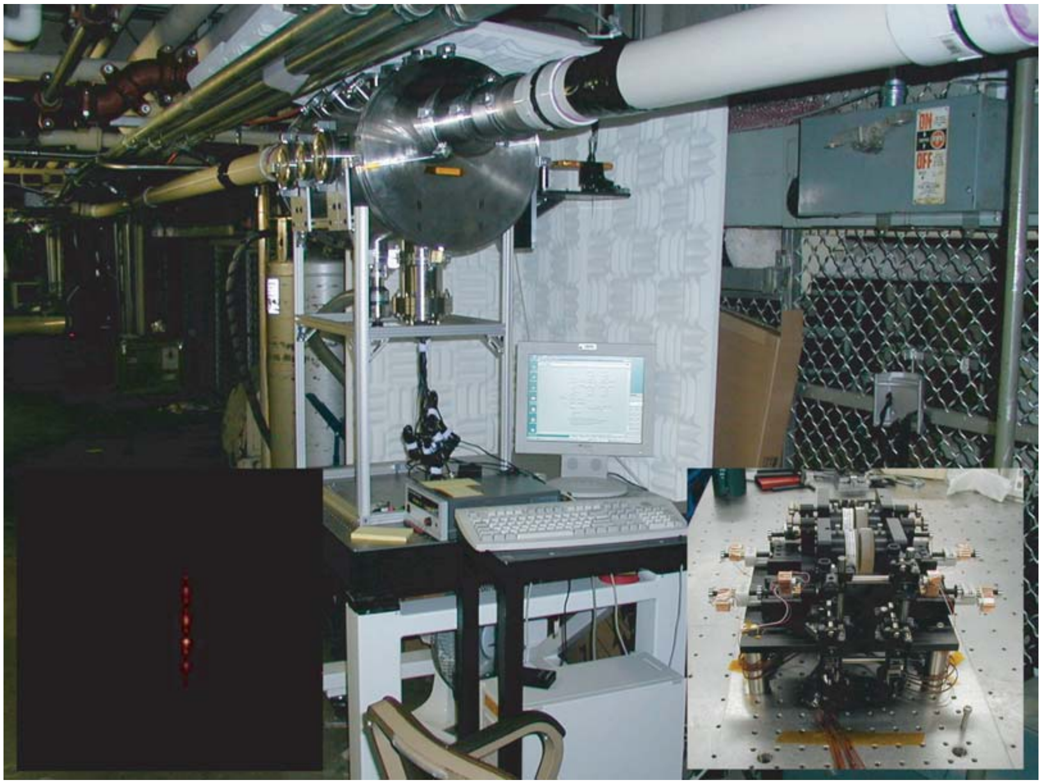
The goal of the Black Hole Imager is to enable direct imaging of the distribution and motion of matter in the highly distorted spacetime near the event horizon of a black hole. This will require angular resolution better than 0.1 microarcsecond—a million times better than Hubble Space Telescope. An X-ray interferometer is naturally matched to this task, since accreting black holes are expected to have a high surface brightness in X-rays, and this, coupled with the short wavelength, allows an instrument of relatively modest aperture and baseline to be used.

An X-ray interferometer with 0.1 microarcsecond (μas) resolution poses technical challenges. At wavelengths near 1 nm, the required baselines are about 1 km, and focal

Strategic Technology Infusion Flow - Black Hole Imager



distances must be 1,000–10,000 km to obtain reasonable detector scales. This means that separate spacecraft are needed with highly controlled formation flying. Nominal requirements are: position accuracy of a fraction of a nanometer, angles known to 0.1 µas, and optical surfaces figured to 2.5 nm.



The Black Hole Imager makes use of X-ray interference (lower left), recently demonstrated in the laboratory.

Pointing. Sensing and controlling the orientation of the line joining the centers of the reflector and detector spacecraft is probably the greatest technology challenge, one shared with the Big Bang Observer and NASA's *Terrestrial Planet Finder* mission. An advanced form of gyroscope may be needed.

Mirror figuring. Though grazing incidence relaxes the required surface figure accuracy, extending current fabrication techniques to panels of the size required for this mission will not be trivial.

To reduce the risks associated with making such large technical advances as these in one step, it would be desirable to first fly a pathfinder mission with angular resolution a hundred times less fine.