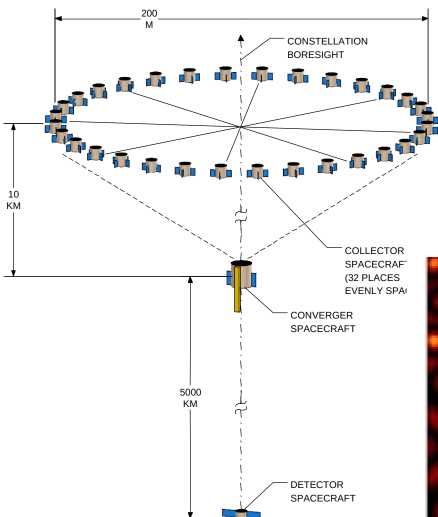
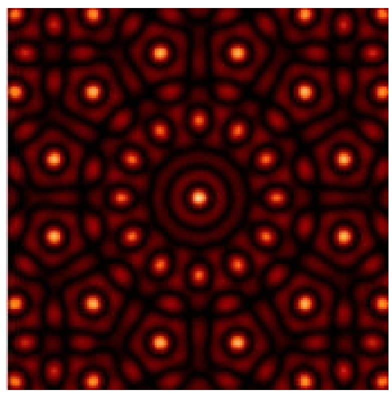
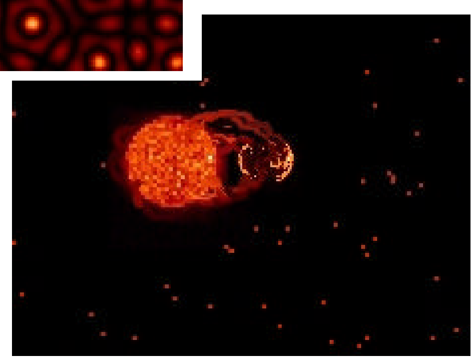
Final Report to the
NASA Institute for Advanced Concepts
January 9, 2000

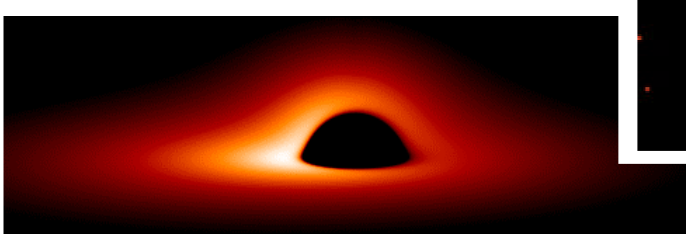
Phase I Study

X-ray Interferometry – Ultimate Imaging









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We also gratefully acknowledge contributions from the Maxim Study Team, chaired by N. White of Goddard Space Flight Center. (see http://maxim.gsfc.nasa.gov).

Cover: The phased array of spacecraft creates a giant telescope. The second panel shows a response pattern. In the third panel is the simulated image of the corona of a close binary star. The bottom panel is a simulation of the x-ray emission from the accretion disk around a black hole.

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OVERVIEW

In this report we review the scientific potential of x-ray interferometry and show how it can be realized in the foreseeable future. With additional study it should be possible to fully demonstrate a reliable technical path to the launch of an exciting new class of scientific mission. We show that angular resolution a million to a billion times higher than that of the Hubble Space Telescope is within our technical grasp.

The x-ray band of the spectrum is the natural band for ultra-high resolution imaging. The sources have very high surface brightness, the features are often very fine, and the short wavelengths allow high resolution in relatively small instruments. The extraordinary improvement in resolution will enable new probes of extreme environments like the warped space-time regions above the event horizons of black holes.

In this report we present some instrument design concepts for the observatory. We tabulate and explain the mission requirements and the instrument tolerances that emerge therefrom. We show with laboratory data that the interferometry can be realistically achieved. A strawman mission concept is proposed.

We review all the component technologies that are needed to put together a full mission. From these we identify which are the key technologies that need attention before a mission can, with confidence, be built.

One major feature of the mission concept is that the resolution can be improved by flying the primary mirrors farther apart to create a longer baseline. As the distance between the mirrors rises, the positional tolerances do not tighten, but remain the same. Thus there is no limit on resolution as long as the system can function across the larger distance. We have studied the limits on resolution and feel that system can function down to a few nano-arcsecond and possibly below.

As it is our purpose to convince NASA that this advanced concept is of use in future missions, we have been directly working with NASA committees this year. The planning committee for the Structure and Evolution of the Universe (SEU) theme has looked at our ideas and as a result added a mission called Maxim (for Micro-Arcsecond X-ray Imaging Mission) to its “visionary missions” category.

I. Goal of the Study

A. THE GOAL

The goal of astronomy is to make the distant appear close, since the extreme distances of the universe obscure our view of its components and hide the workings of nature. Through the use of telescopes astronomers have improved our vision -- physical understanding of the universe has followed. The Hubble Space Telescope represents the greatest clarity of vision ever achieved by a major observatory at visible wavelengths. The 0.1 arcseconds resolution it achieved is 600 times finer than that experienced with the naked eye. The results have been stunning. Intercontinental baseline radio interferometry has produced images with milli-arcsecond resolution, one hundred times finer than HST. With these images, astronomers have probed deep into the hearts of quasars and the Milky Way Galaxy, but have mostly been limited to highly non-thermal sources.

Astronomers are nowhere near reaching the practical limits of imaging. Many orders of magnitude improvement are possible across much of the electromagnetic spectrum. To achieve higher resolution, the astronomer must move to larger aperture telescopes or longer baseline interferometers to suppress the effects of diffraction. However, as the quality of the image improves, the telescope must be built large enough to collect an adequate signal. Thus the three basic parameters for approaching the ultimate in imaging are wavelength, baseline, and collecting area.

It is the goal of x-ray interferometry is to study hot, thermal sources with resolution at least as good as 0.1 micro-arcseconds (μas) – one ten millionth of an arcsecond. The unique properties of the x-ray sky together with the power of x-ray interferometry make this goal realistic in the near future.

B. THE OPPORTUNITY OF X-RAY INTERFEROMETRY

What limits the quality of astronomical images?
Answer: Collecting Area and Optical Quality

Our ability to study the Universe is limited only by the quality of our information. Astronomers are famous for relentless pursuit of improved instrumentation. The improvements separate into two areas – larger collecting area and increased resolution.

Collecting Area

For centuries astronomers were mostly concerned with improving the collecting area of their telescopes. The resolution of their images was limited to about one arcsecond by the twinkle of the atmosphere, so area was the only parameter they could improve. Unfortunately, this meant ever larger lenses and mirrors, and ever larger expenses. But, the bigger collecting area meant the ability to see fainter objects, pushing the power of the instrument.

When HST became the first major observatory above the atmosphere it was able to make spectacular observations despite a relatively small collecting area because it had higher resolution and lower noise, thereby improving signal-to-noise.

When constrained to the visible, the only way to improve signal is build a larger optic. However, with NASA's ability to send telescopes above the atmosphere, another opportunity arises, namely observe the objects where they are brightest.

With certain exceptions (like extreme synchrotron sources in the radio and lasers in the visible) the brightest sources at any given temperature are thermal blackbodies. Thus they emit with a brightness of

$$B_\nu = 1.8x10^{-5}T^4 \text{ erg/cm}^2\text{/s/ster.}$$

The surface brightness of an optically thick object rises as the fourth power of its temperature as viewed from Earth. Even after adjusting for quantum energy, the photon flux rises as the third power of the temperature. Thus a 5 million degree blackbody is a trillion times brighter than a 5 thousand degree object the same size. It emits a billion times more photons.

X-ray astronomy has a reputation for dim sources. However, these fall into two classes. Some of the sources, like supernova remnants, are optically thin, and thus have low surface brightness. Others, like the inner parts of accretion disks or the surface of neutron stars are optically thick (or nearly so). This makes them among the brightest sources in the universe, in the true sense of the word brightness. The reason that X-ray sources are less luminous is that they are small. However, that makes them ideal targets for super-high resolution imaging.

The maximum affordable collecting area is somewhat a function of the band for which it is built. However, most large telescopes (10 m diameter) have about one million square centimeters of collecting area, and observations of 10,000 seconds are typical for a multi-use observatory. Thus a grasp of 10^{10}cm^{2}s is near typical. Certainly one can argue that larger telescopes are feasible in some bands, but the exact size is unimportant. The wavelength band is the important determinant of the ultimate limit.

Assuming a grasp of 10^{10}cm^{2}s, and a requirement of 100 photons detected per resolution element, we find that the minimum detectable feature size (θ_{min}), scales as $T^{-1.5}$. Such a strong function of temperature indicates that ultra-high resolution imaging is more tractable at high temperature and high energy.

In Figure 1.1 we show this effect graphically. As the temperature of an object rises, for a given grasp, the minimum detectable feature size drops dramatically, while the required baseline rises only slowly. For example, in M87, at a distance of 15Mpc, the smallest feature size detectable in the visible would be 1.7×10^{-15} radians in extent, or 7.6×10^{10}cm, about the radius of the Sun. However, in the X-ray, the angular limit would be 5×10^{-20} radians, or about 22km! The baseline for the visible observation would have to be around 400,000km, the distance from the Earth to the Moon. The baseline for the vastly more powerful X-ray image would be larger, about 12 million km.

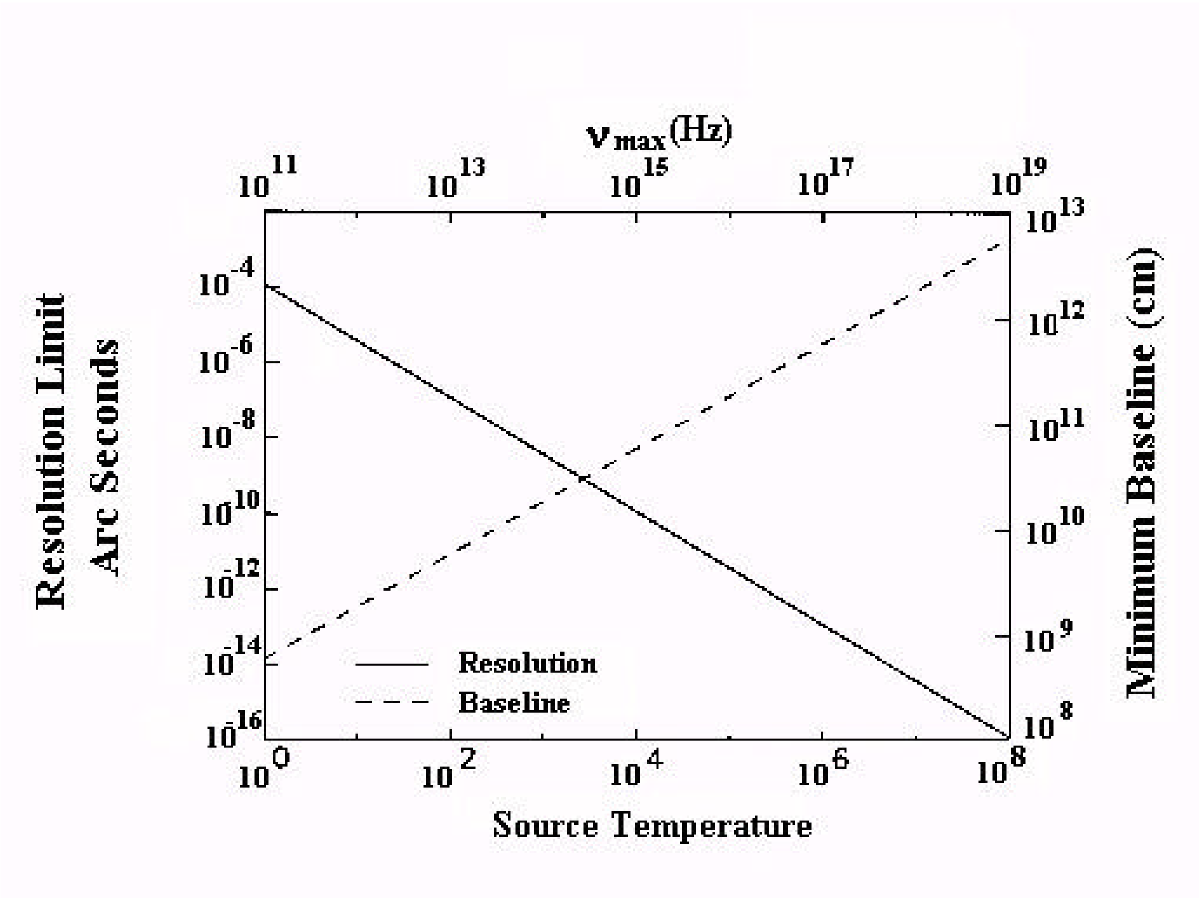

Figure 1.1: At plot of the minimum detectable angular blackbody feature with a reasonable size telescope as a function of temperature. Also shown is the baseline needed to resolve that feature. It is clear that the x-ray band provides the greatest resolution with only modest increases in baseline.

Of course, X-rays images differ greatly from visible images. X-rays are emitted only under conditions considered extreme by humans. Temperatures of millions of degrees and magnetic fields of millions of Gauss can create X-rays. They are often associated with the dramatic events heralding the both the birth and death of astronomical objects. As such, they come from compact regions and image the core structures in some of the most interesting events in the universe. This is the antithesis of structures viewed in radio VLBI, which are usually created by high energy electrons expanding away from the central structure. With X-rays we see the central engine itself.

The Diffraction Limit

From the surface of the Earth, the turbulence of the atmosphere limits the quality of our images. From space, however, it is only the quality of the instrument itself that matters. If the mirrors themselves are made sufficiently well the fundamental limitation in the clarity achieved by the telescopes is to be found in the diffraction limit.

The diffraction limited resolution R of a telescope (in arcseconds) is given by:

$$R = \frac{l}{36000D}$$

where λ is in Angstroms, and D is in meters. For example, HST has a 2.5 meter diameter and at a wavelength of 5000Å has resolution of 0.055"

To push beyond the diffraction limit, one must build an interferometer. Two or more optical elements are placed at a large distance, and the beams combined in some fashion that does not lose their phase information. When this is accomplished, one can build a synthetic aperture with a resolution set by the separation of the optics as opposed to their size. This allows one to achieve very high resolution without building impossibly large optics.

VLBI uses a wavelength of $2x10^8$Å on a baseline of 10^7m to achieve .001 arcseconds. HST, with a 2.4m aperture at 5000Å achieves 0.1". The planned Space Interferometry Mission (SIM) uses 5000Å on a 20m baseline to achieve resolution of .01". In the X-ray, where wavelengths can be as short as 2Å, it takes a one millimeter aperture to match HST, a one centimeter aperture to match SIM, and a full 10cm aperture to match intercontinental baseline interferometry in the radio. Truly, the diffraction limit is a much smaller problem in the X-ray, if optics of appropriate quality can be built.

So why do X-ray astronomers live and work with among the poorest quality images of any spectral band? The recently launched Chandra Observatory represents the state of the art in X-ray observatories. Its resolution of one arcsecond, and collecting area of a few thousand square centimeters can be matched in the visible portion of the spectrum by a mail order telescope selling for under $1000. The problem is that X-ray optics must use grazing incidence and two reflections off hyperboloid and paraboloid surfaces. These Wolter type I optics, with their quasi-cylindrical surfaces, are very expensive and difficult to figure and polish. To date, a diffraction limited X-ray telescope has not been built.

In this document we show that x-ray interferometry is possible. Application of non-traditional approaches to interferometry allow us to achieve the needed optical precision and create synthetic apertures in the x-ray. Once this is accomplished, very high resolution is possible on modest baselines, and the bright x-ray sources provide ideal targets.

C. NASA PROGRAMMATICS

As part of its mission to Explore the Universe, NASA has always maintained an aggressive program in space astronomy. X-ray interferometry will fit naturally into this program. The huge advances in resolution will provide unparalleled views of deep space, making objects appear a million times closer.

X-ray interferometry can be so powerful that it will:

- resolve the event horizon of a supermassive black hole in a quasar,
- observe a 100km emission knot on the surface of Alpha Centauri,
- image the disk of a star in the Magellanic Clouds,
- map the accretion disk at the center of the Milky Way in detail.
- directly measure the parallax of a star in the Virgo Cluster of galaxies,
- resolve one tenth of a light year at the far extent of the visible universe.

These parameters sound like science fiction, but actually represent a capability that we can pursue today.

From a programmatic perspective x-ray interferometry is also a good fit. Like all x-ray astronomy, it can only be done from space. However, it provides some challenges to NASA's engineering expertise, including:

- Precision formation flying of multiple spacecraft
- Interferometric pointing control of spacecraft
- Active metrology for high internal spacecraft stability
- Stable drift-away orbital environments
- High precision target acquisition

Luckily, our requirements do not stand alone. All of the above challenges are also being addressed by other missions in NASA's plans. Chief among these are ST-3, LISA, and SIM.

During the duration of this study we have been active in working with NASA to promote the ideas of x-ray interferometry. We have worked closely with NASA's Maxim team, and have membership overlap. Maxim stands for Micro-Arcsecond X-ray Imaging Mission, and consists of a committee chaired by Dr Nicholas White of Goddard Space Flight Center. We have shared the results of our work with them, and they with us. Further information is available on their website at http://maxim.gsfc.nasa.gov.

The Maxim team, during its period of activity, spent more time identifying key science projects than we have in this study. There was a general consensus in the Maxim review that the natural scientific goal should be to image the event horizons around the black holes in active galactic nuclei. By joining forces with the Maxim group, we have been able to make progress in the acceptance of X-ray interferometry as a future mission for NASA. In recognition of this, Maxim now appears as "New Visions" candidate instrument in the long term roadmap for NASA in the 2015 and beyond time period.

The Maxim group was less directed toward pushing the visionary aspects of instrumentation to its natural limits. Maxim spent no effort on studying science and technical realities substantially below one micro-arcsecond. Similarly, they had no resources for studying the realities of the mission concepts, so our contribution has been crucial to this preliminary acceptance by NASA. The Phase II support from NIAC can now give NASA confidence that Maxim and X-ray Interferometry in general will become fully realizable missions in the right timeframe.

II. Requirements

A. TARGET PROPERTIES

Over the past 10 years the study of black holes has moved from a quest to prove their existence, to detailed studies of their effects on space-time and testing the of physics under extreme conditions. This change in emphasis has been driven by X-ray, optical, and radio breakthrough observations. These have established that stellar mass black holes in our galaxy and supermassive black holes (millions to billions times the mass of our Sun) at the nucleus of galaxies are relatively commonplace.

An entirely complementary and more powerful method of examining these black hole laboratories would be to take an actual picture. The ultra-high resolutions required (1μas or better) have, until now, been viewed as prohibitive, but the realization that X-ray interferometry is feasible puts this holy grail of X-ray astronomy within our technological grasp. Such images would provide the ultimate proof of existence of these most extreme objects. They would allow us to study the exotic physics at work in the immediate vicinity of black holes—the physics of the innermost accretion disk, hard X-ray emitting corona, the formation of relativistic jets, and the "plunging" region in which material undergoes the final spiral through the black hole magnetosphere towards the event horizon. These images would be amongst the most influential scientific images of the new century.

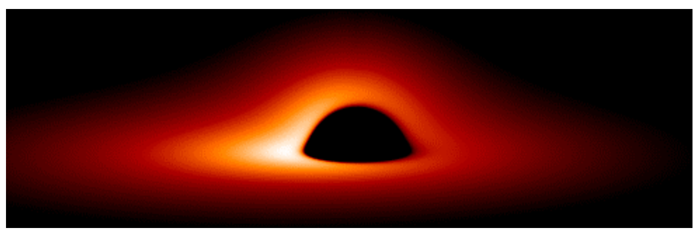

Figure 2.1: Simulation of the distribution of x-ray emission from the inner accretion disk of a black hole. The warped shape is due to the orbits of the photons over the top of the hole. The dark spot is the plunging region where Keplerian orbits fail.

The quest to image a black hole would capture the imagination of scientists and the public alike. While it may seem contradictory to image an object from which light cannot escape, the black hole can be seen in silhouette against the hot material spiraling toward the event horizon. We would directly observe light from the accretion disk bending around the black hole and so see the actual distortion of space-time by the intense ultimate gravitational field. The best candidate black holes to observe are the nearby active nuclei (AGN). For example the AGN in M87 is believed to harbor a 100 million solar mass black hole at a distance of order 1 million parsecs. Depending on whether the black hole is rotating or not, an angular scale of 3 to 6 micro arc-seconds is required to resolve the event horizon of the supermassive black hole in M87.

It is worth noting that the capabilities of MAXIM would be such a huge leap forward, that it would have an enormous impact in all areas of astronomy, not only the study of black holes. We could capture detailed images of the coronae of other stars, map the plasma activity in newly forming stellar systems, follow the motions of material ejected in supernova explosions, and watch material cooling at the center of clusters of galaxies.

B. BASELINE

The resolution of the interferometer scales with the baseline between the extreme ends of the interferometer. The resolution is given by:

$q = \frac{l}{2B}$ where B is the baseline.

Figure 2.2: Artist's conception of the shared corona of a close binary star as imaged by an interferometer in the x-ray.

In this table we show some characteristic targets and their angular sizes. We can think of nothing smaller than a neutron star that is likely to be of particular interest, so a baseline of 10,000km appears to be about the maximum we should consider.

Table 2-1: Targets and their Characteristic Sizes

Target	Angular Size (radians)	Baseline at 10Å
Sun at 1pc	$5x10^{-8}$	1cm
AGN Accretion Disk	$5x10^{-10}$	1m
AGN Event Horizon	$5x10^{-12}$	100m
Binary Accretion Disk	$5x10^{-14}$	10km
Neutron Star	$5x10^{-16}$	1000km

Baselines of up to a meter can be handled in a single spacecraft. Above a few tens of meters we need to place the optics on separate spacecraft. But, to truly achieve the potential of x-ray interferometry, we should use the separate spacecraft, allowing us to fly from as close as 50m baselines to as far apart as 1000km. Our minimum acceptable is 100m, and the maximum needed is 1000km.

C. COLLECTING AREA

The collecting area required of the observatory can be estimated on very simple grounds. Choosing an exact size and bandpass will come later, so we need only be approximate for now.

A mission with just one square centimeter would be able to get a few high quality images by spending days per target. We risk the target itself changing during that time, so we need more area. $10cm^2$ is better. The Einstein observatory was able to collect a substantial number of quality images with just $5cm^2$, so this represents an absolute minimum. However, we would not be able to perform serious work on many classes of target. At $100cm^2$, we can observe a fair number of targets in every category. However, for most targets there will be a dearth of photons. At $1000cm^2$ we would match the collecting area of Chandra, and be able to acquire high resolution images on many objects. At $10,000cm^2$ we would not only have enough area to fill in the pixels on high resolution images, but enough signal to separate into energy resolved images and time-resolved images. This would allow us to watch and analyze real-time events like flares on stars and redshifting matter falling into black holes.

It is clear that we should place $10,000cm^2$ as our goal, and recognize that excellent observatories could be realized with substantially lower area.

D. IMAGE CONTRAST

Image contrast is not a major driver of the instrument design. For the most part, the quality of the results does not depend on being able to observe faint features close to bright ones. Achieving 10:1 ratios between signal and noise requires only 50% control of the intensity of the mixed beams. To achieve 1%, still requires only 20% control. This is easy to achieve and maintain, and perfectly acceptable for the images needed.

E. FIELD OF VIEW

The field of view requirement is again related to desired image quality. A 10x10 image is hardly better than a tic-tac-toe board and is unacceptable. A 100x100 image would be just fine. At 1000x1000 we approach the image quality of HST. Thus, it is clear we require a field of view of 100x100 resolution elements, with a goal of pushing higher, to 1000x1000.

III. Solutions to the Problem

A. SPHERICAL MIRROR X-RAY INTERFEROMETRY

In this section we present some of results on high resolution telescopes for the X-ray and some techniques that can lead to practical X-ray interferometry in the near term.

First Achieve the Diffraction Limit There is no point in building an interferometer until one has reached the practical limit on size for a single optic. A 3m mirror at 2 degrees of graze yields a 10cm aperture. 10Å radiation entering a diffraction-limited optic with a 10cm aperture experiences diffraction at the 2 milli-arcsecond level. The optic would have to maintain somewhat better figure than a diffraction limited visible telescope. The wavelength is one thousand times shorter, but the graze angle buys back a factor of thirty. Thus, where one might specify a $\lambda/4$ optic in the visible, one will need a $\lambda/120$ optic for the X-ray device. Such tolerances are challenging, but well within the current state of the optical art.

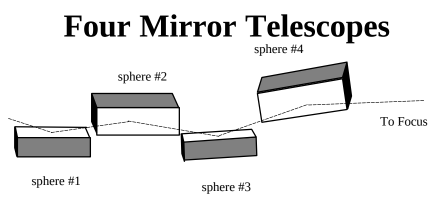

Figure 3.1: Four mirrors properly configured and mounted in sequence can create very high quality x-ray images at modest cost.

Thus, if high quality mirrors suitable for X-ray astronomy can be built, the diffraction limit can be reached. We have recently developed and demonstrated a technique that allows us to build X-ray optics to exacting tolerance. This patented idea (Cash, US patent #5,604,782 [1997]) involves using conventional, normal incidence mirrors at grazing incidence. It turns out that it can be shown that the primary aberrations can be removed by a sequence of four or mirrors. Similarly, magnification of the focal plane is also possible. Since the optics required are no longer extreme aspheres, they are

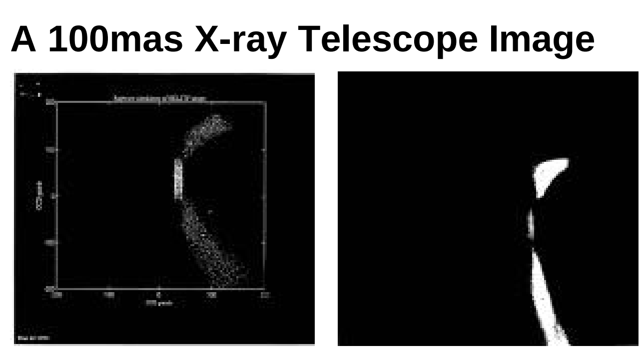

Figure 3.2: Parallel bars were imaged at 13.3Å using the telescope in Fig xxx-1. To the left is a simulation of what was expected. To the right is the actual image. Resolution near 0.1” was reached.

much cheaper and of much higher quality than Wolter class optics. Extensive raytracing shows that this design class can nicely support interferometry. The single telescope can reach 20mas (milli-arcseconds) for a 30cm optic, rising to 2mas for 3m optics. Thus, these telescopes are providing a breakthrough in their own right.

We know for a fact that the approach works and will be able to adapt it because, we have built and tested a four-element system that approached the diffraction limit. (see Figures 3.2). Gallagher et al (SPIE, 1996) report the first laboratory version of the spherical mirror telescope. Our newest results show good modulation all the way down to 0.1 arcseconds in our test telescope. NASA is supporting its application in building a sounding rocket to image X-rays at the 0.1" level.

Mix Two Beams There is more than one possible approach to interferometry, but the one I find most attractive is the Michelson Stellar Interferometer approach (Michelson, A. A., 1920, ApJ, 51, 257, Cash, W., 1994, Proceedings of the International School of Space Science). It is particularly attractive in its simplicity. Two beams from co-aligned telescope apertures are mixed in the focal plane - nothing more. This is the approach in use for visible light interferometers, and it is directly applicable in the X-ray as well. Inasmuch as studies of the Space Interferometry Mission (SIM, Pre-Project Mission Information Document, JPL, 1996), show that astrometry is possible at the micro-arcsecond level, the same tolerances applied to an X-ray telescope would provide X-ray imaging at the micro-arcsecond level.

To achieve the synthetic aperture that is the goal of interferometry we must mix the beams from two grazing incidence optical paths in the focal plane. Each beam should be operating at the diffraction limit, and fringes will appear in the focal plane, in the classical, two slit Fraunhoffer way. To observe the fringes, however, one must have monochromatic light, and pathlengths between the two telescopes that are close to equal.

Fringes from different wavelengths have different frequencies and will thus wash out if allowed to mix. Similarly, as the optical pathlength difference to the focal plane grows, the sensitivity to small differences in wavelength grows, making the monochromaticity requirement tighter. A CCD has $E/\delta E$ of nearly 20 at 1keV, supporting 20 fringes across the image. A hypothetical imaging quantum calorimeter with 1eV resolution could support a thousand fringes.

Improvements Shift To Mechanical Away From Optics. Once one has built two diffraction limited optics and mixed the beams to create fringes, improvements no longer come from the optics. There is little incentive to improve the quality of the mirrors. Consider, for example, that the optical surfaces of the radio dishes

Schematic of Interferometer

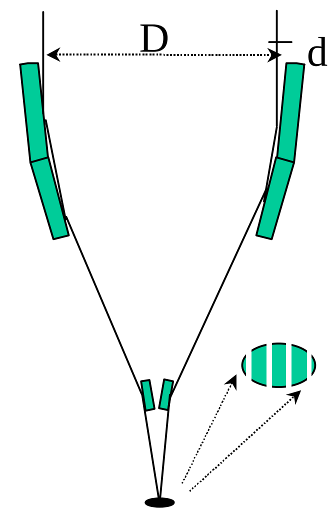

Figure 3.3: The beams from two independent x-ray telescopes can be mixed to

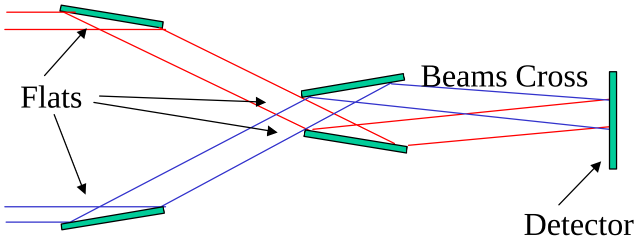

Figure 3.4: Basic arrangement of flat mirrors at grazing incidence that creates a practical interferometer.

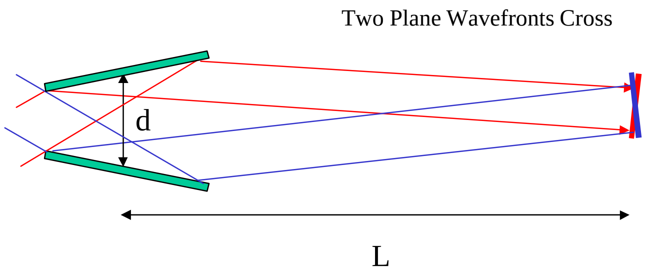

Figure 3.5: A beam mixer can be made from two grazing flats. This converger uses distance to mix the wavefronts at a low angle.

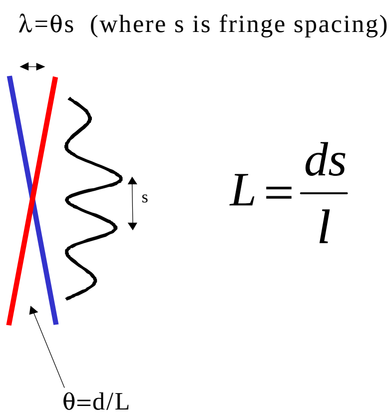

Figure 3.6: The fringes spacing is amplified on the detector where the two wavefronts cross.

used in intercontinental baseline interferometry are made of coarse, unpolished metal, and fall many orders of magnitude short of milli-arcsecond optical quality. Once below the diffraction limit, the quality of the mirror does not need to improve.

We wish to stress another very important point. As the baseline increases, and the resolution rises, the metrological and pointing tolerances do not tighten. They remain the same. While it is true that, as a percentage of distance, the positional tolerances tighten, on an absolute scale they do not. This means that in the case of a multiple spacecraft interferometer, once the distance between spacecraft is measured and maintained to a desired fraction of laser light wavelength, the distance is unimportant.

Once the system is built, the mirror array components can be placed as far from each other as we wish. As long as our knowledge of their pointing and separations are maintained, the resolution is without fundamental limit. It is true that the radiation will start to blur out, missing the detector and lowering the effective area, but the system still works. This makes the potential of X-ray interferometry truly staggering. A pico-arcsecond interferometer may not be a whole lot more difficult than a micro-arcsecond system!

B. FLAT MIRROR X-RAY INTERFEROMETRY

We have recently realized that there is a highly practical means for mixing the X-ray beams, without a fancy beam splitter. The principles are well established and recognized; we have just discovered their suitability for grazing incidence optics. The idea is to create two diffraction limited wavefronts, and steer them together at a small angle, as shown in figures 3.4, 3.5, and 3.6. In the figures we show a flat wavefront from infinity impinging on two flat mirrors. These flats must not disturb the wavefront, meaning they need to be about λ/100 or better (where λ is 6328Å). This is better than the average flat mirror that

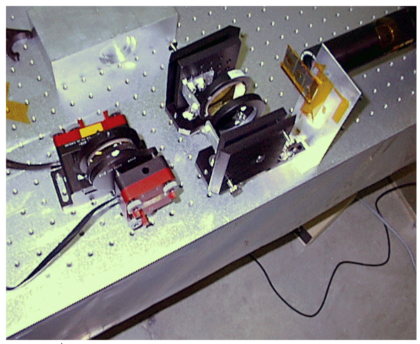

Figure 3.7: Photo of 1st Flat Mirror Grazing Incidence Interferometer

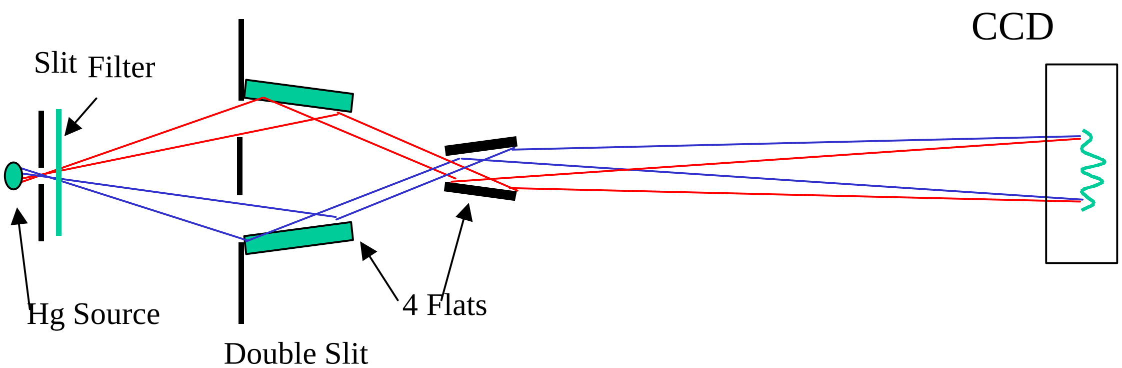

Figure 3.8: Schematic of Interferometer Showing Entrance Slit Needed for Incoherent Light

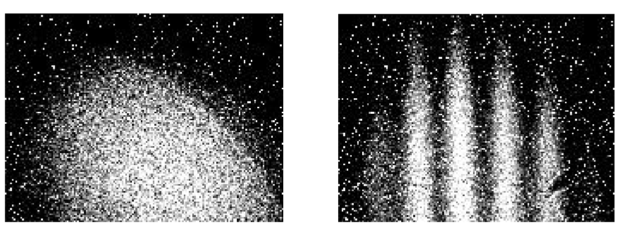

Figure 3.9: Results with visible light (Hg green line) show that the fringes are the result of interference between the two channels, and that the system works with incoherent light as well as with lasers. To the left is the image with one channel illuminates. To the right, the fringes become clear when two channels are illuminated.

one purchases, but well within the state of the art. These flats steer the beams onto a second pair of flats that re-direct the beams into quasi-parallel convergence.

The idea of this beam converger is to cross the beams at the detector at a very low angle. This leads to large fringe amplification. The wavelength of the fringes on the detector is then given by $\lambda L/d$, where d is the separation of the secondary mirrors and L is the distance from the mirrors to the detector where the beams cross. If L/d is large, the fringes can become large.

This is an approach to creating interferometric fringes that actually makes use of the low graze angles associated with X-ray optics. It turns out to be highly robust. The assembly tolerances are more forgiving than conventional normal incidence optics, and the lower graze angles lead to larger fringe, higher throughput and greater mechanical tolerance.

An essential step in establishing the viability of X-ray interferometry as a discipline for astronomy is the demonstration of a practical X-ray interferometer. The interferometer must not only create fringes, but be of a design class that can be developed into an efficient system for astronomy.

There have been very few X-ray interferometers successfully built. While there is no question that X-rays will exhibit the same wave properties that light exhibits in other bands, the extreme shortness of the waves has made development of a practical interferometer very difficult. In 1932, Kellstrom used a Lloyd's Mirror geometry to create X-ray fringes (Nova Acta So. Sci. Upsala, vol 8, 60). This setup, while creating fringes and demonstrating the principle, is extremely inefficient in collecting area, requiring the mirror to operate at a vanishingly small graze angle (i.e. below one arcminute). In 1965 Bonse and Hart (App. Phys Lett, Vol 6, 155) showed that one could use a chain of Bragg crystals to create X-ray fringes. Because of the extreme inefficiency of Bragg crystals, this class of interferometer would be incapable of observing faint celestial sources.

We have now built and successfully tested an X-ray interferometer of a class that can have practical applications. In this section we describe the experiment and show the

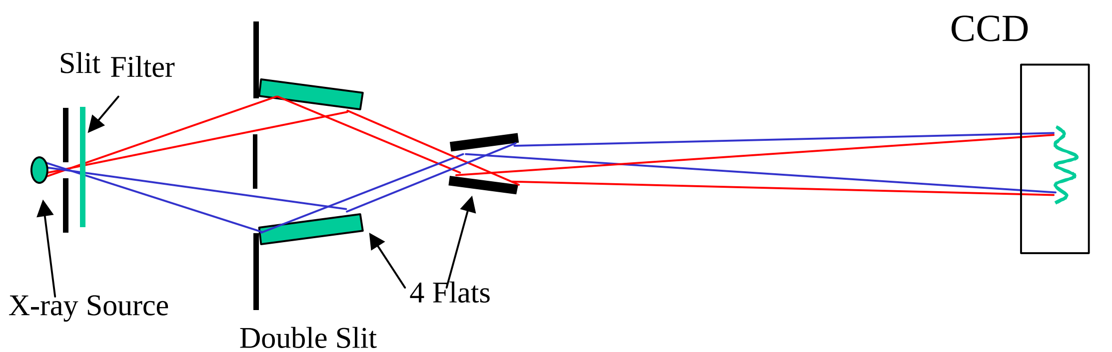

Figure 3.10: Schematic of the interferometer used to create x-ray fringes.

results.

Instrument Design

The instrument is of the simple four flat mirror design shown schematically in Figure 1 below. The work was performed in a 120 meter long vacuum facility at the Marshall Space Flight Center. We used a Manson electron impact source with a magnesium target and 2 micron aluminum filter to create a beam that consists mostly of the Mg K line (1.25keV). The beam passed through a 5 micron exit slit.

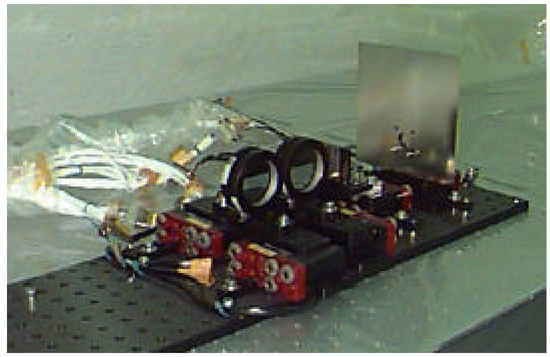

Figure 3.11: Photograph of the four flat mirrors on their manipulators.

Sixteen meters from the slit the divergent beam entered the interferometer. An entrance aperture that consisted of two parallel slits ensured that the two primary mirrors were illuminated, but that none of the direct beam could enter the interferometer without reflecting off the optics. After passing the double slit, the wavefronts reflected on the primary mirrors. Each mirror was a 50mm circular optical flat mounted at about 0.25 degrees to the incoming beam. Each was mounted in a precision manipulator that allowed fine rotational and translation adjustment from outside the vacuum tank as shown in Figure 2. They were set 0.769mm apart at the front and 0.551mm apart at the back. The primary mirrors created reflected wavefronts that crossed and were then reflected by the secondary mirror.

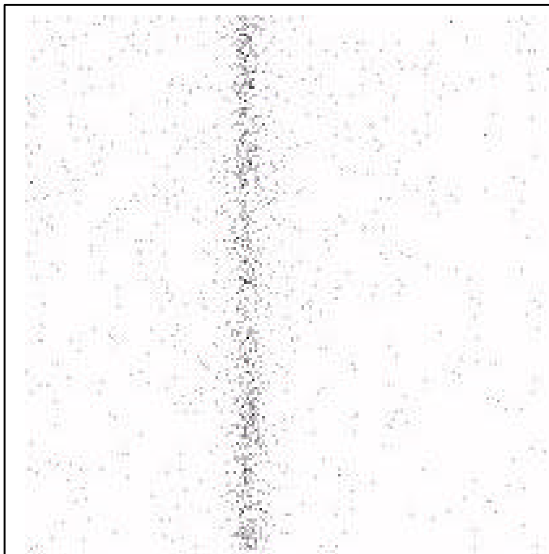

Figure 3.12: CCD image taken in the x-ray. The stripe of events is the projected aperture of the grazing incidence flats. At a distance of 100m, the sub-millimeter width of the stripe already indicates high resolution performance.

The front of the secondary mirrors was 16.97mm beyond the back of the primaries. These mirrors were also 50mm diameter circular optical flats mounted on manipulators. They were set 0.40mm apart at the front, and 0.618mm apart at the back. The wavefronts, when they emerged from the secondary mirrors, were very nearly parallel. They then traveled 100 meters down the vacuum pipe where they were detected by a CCD. The CCD had 18μ pixels, was liquid nitrogen cooled, and operated in an individual photon detection mode.

When the system was turned on, each of the two beams created a vertical stripe of illumination on the CCD about a millimeter wide. The final step was to fine adjust the angles of the secondary mirrors so that the two stripes fell on top of each other at the CCD.

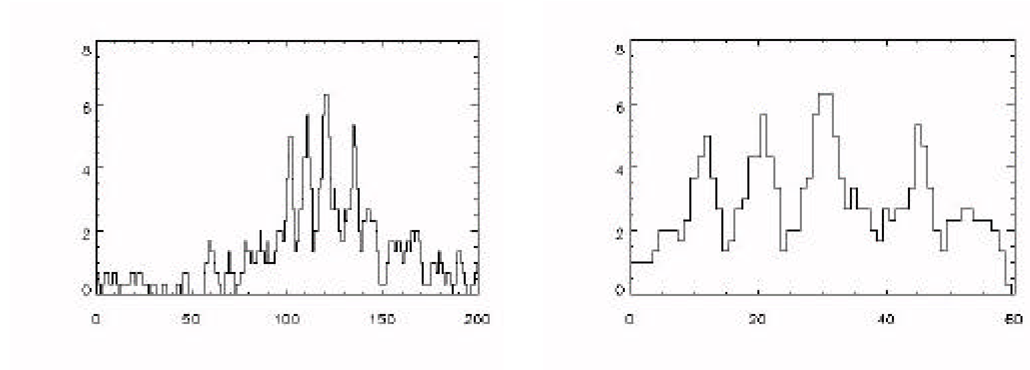

Figure 3.13: To the left is a histogram of the events in the stripe over the top half of the image. A two-bin boxcar smooth has been run over the histogram to suppress Poisson noise. To the right is a magnification of the central fringes, so that on can properly see the individual pixels of the CCD.

On the first attempt (March 8, 1999) we found that one of the channels was too wide on the detector. We eventually tracked this to a mirror that had shifted in its mount during shipping, and had become slightly warped. We returned to Colorado, reseated the mirrors and then returned to Marshall Space Flight Center.

On the second attempt we were successful. Figure 3.11 shows an image of the CCD with the stripe of illumination clearly visible. Within the stripe of illumination are the fringes we were seeking. When the illuminated region is collapsed into a histogram of events across the x direction, we find the result in Figure 3.12. The histogram is for the upper half of the CCD only. A two bin boxcar smooth has been run across the data to suppress the Poisson noise.

Further analysis of the images show that the fringes are not completely well behaved. In Figure 3.12 one can see that the fringe on the right is a little bit farther apart than the others. This is the result of a 25nm deviation from flat in one of the mirrors near its edge. There are other deviations from flatness in the mirrors that lead to fringes that are not perfectly straight and parallel. This is not a surprise as we are using “λ/20” flats from a catalogue. We set the mirrors at 0.25 degrees partly to suppress the surface irregularities.

With this first system we were able to accomplish our goal, to create fringes in an optical setup that is appropriate for development into a full-fledged astronomical system. The sensitivity of the fringes in this setup indicated we achieved sensitivity to angular scales near 0.05 arcseconds.

However, with this initial success comes the question of what to do next. Several things are evident.

C. USING IN-PHASE FLATS

A geometry that has particular appeal as a variation on the simple pair of flats is to place a series of flats in a circle around a common center as shown schematically in Figure 3.14. Each pair of opposing flats creates fringes. However, every pair of flats, even those not opposed interfere at a different frequency as shown by the set of intersecting lines in the Figure 3.14.

We have simulated the effects of using multiple flats held in phase, and the results are not

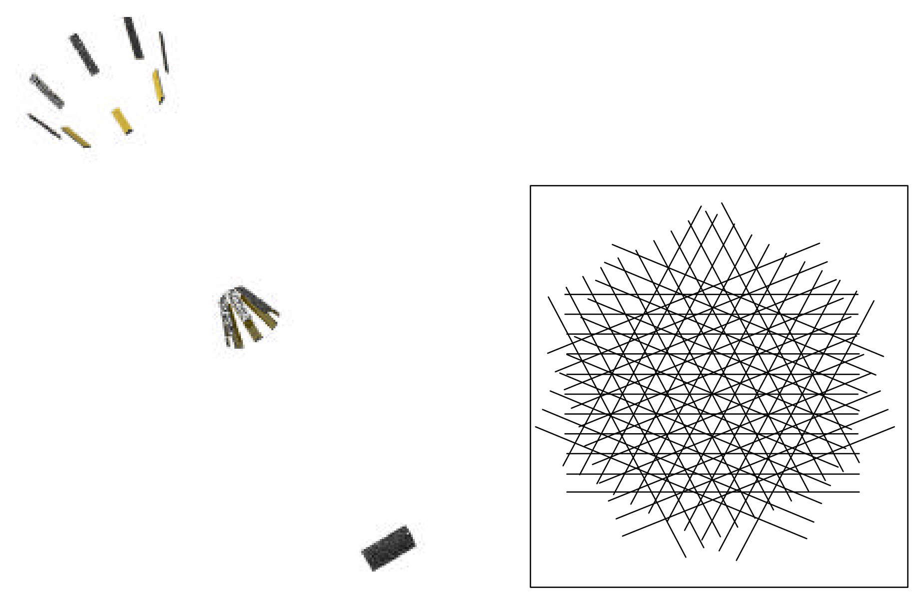

Figure 3.14: The schematic to the left shows a circle of flat mirrors feeding a second circle of flats. The resulting beams mix at the detector. To the right we see that a complex pattern of fringes is created in two dimensions on the focal plane.

only artistic, but interesting. In figure 3.15 we show the response in the focal plane as a function of the number of flat mirrors. With one pair we see the familiar fringes. The addition of just two more mirrors changes the point response function to a square array of points. With eight or more mirrors, the point response function becomes a complex pattern of circular structures. However, as the number of mirrors increases, the secondary peaks are driven farther away from an ever-brighter central point.

As the array of flats is pointed around the sky, the point moves around the field of view. This is exactly the same behavior a point source a point source exhibits in the field of a telescope as the pointing changes. We can create direct images in this interferometer without recourse to image reconstruction in a computer. In some sense we are building a diffraction-limited telescope out of a phased array of flats!

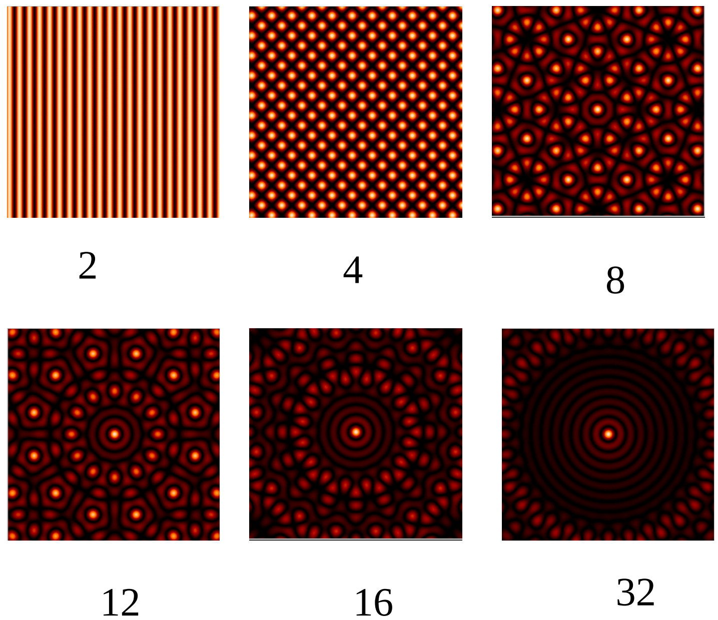

Figure 3.15: Simulations of the beam patterns at the focal plane for a circle of flat mirrors. With just two mirrors, simple fringes appear. With more mirrors the patterns become more complex. As the number of mirrors gets large, behavior similar to a telescope starts to emerge.

The diameter of the clear area around the central peak is roughly equal to the number of mirrors. That is, if 32 flats are used in the array, then the field of view will allow 32x32 diffraction limited spikes in the field. So, 32 mirrors set around the diameter of a one meter circle, operating at 1nm (1.2keV) will achieve a resolution of 10-9 radians (0.2 milli-arcseconds) in the central point, and a full image of a region 6.4 milli-arcseconds square will emerge on the detector. If the beam is wide enough, the image can extend farther from the center but will experience some confusion that will have to be removed by image manipulation.

This system has a huge advantage as it automatically multiplexes many different frequencies against each other, to suppress spurious peaks, and automatically create an image. The biggest disadvantage is that the individual mirrors must all be nulled so as to provide equal path length for the beam, and they must be held in null during the observation.

D. USING CONCENTRATORS

The biggest single disadvantage to using flat optics is the distance required between the converger and the detector. To magnify the fringes from one wavelength (1nm) to the 100µ detectable with most detectors requires a convergence angle of 10^{-5} radians. Thus, if the beams are even 1cm square, the distance from converger to detector must be on the order of 1km, necessitating two spacecraft.

However, it is possible to build the interferometer in a tighter space. The angle of convergence cannot be reduced, but the size of the beam can. If we used curved-surface optics to concentrate the beam without destroying the diffraction limited wavefront, then the image can be reduced in size and the detector brought closer to the converger. This, of course, requires that we build diffraction-limited telescopes that concentrate the radiation.

Use of spherical mirrors in a Kirkpatrick-Baez mount can achieve the needed quality. Other approaches, such as Wolter optics, also work in theory but are difficult to build. The AXAF mirrors approach the needed quality, indicating that Wolters remain viable.

We show a simple schematic in Figure 3.16 that minimizes losses. The first mirror concentrates the light onto a small secondary mirror that re-collimates the beam and simultaneously acts as a converger. Thus the system is, in principle, the same. All the other considerations remain as before. The main achievement is a compact structure at the cost of optical complexity. Another significant advantage is that, with the physically smaller field of view, the internal detector background will be lower.

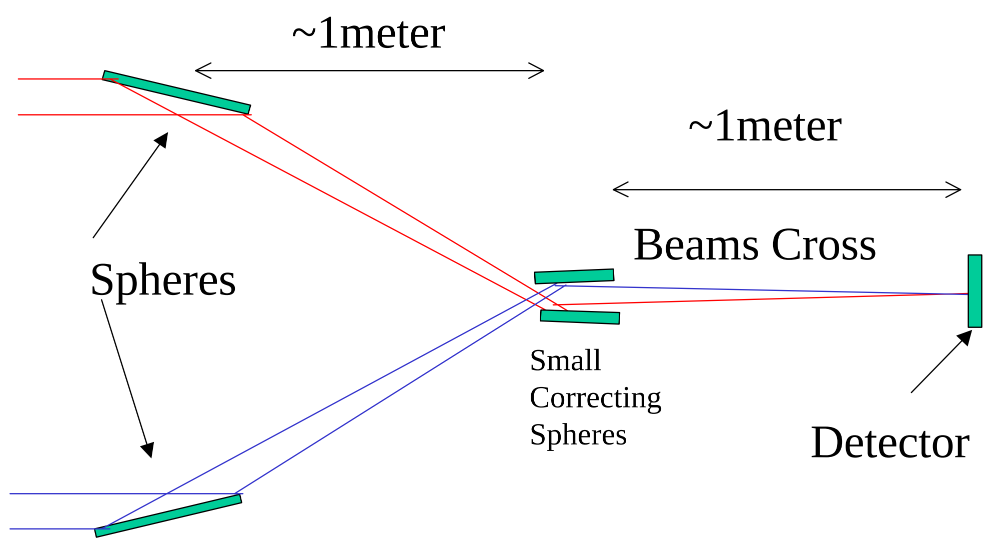

Figure 3.16: By replacing the flats with curved surface mirrors the beam can be concentrated as it is converged. These optics are significantly more difficult to build than simple mirrors.

One side effect of the concentrator is that each mirror must remain fixed in its focal position. In the flat mirror system it is possible to physically change the separation of the flats, thereby changing the resolution of the system. This, of course, can be solved by using moveable flats to re-direct the wavefronts into the concentrating optics at the cost of extra complexity and signal loss.

Overall, the choice of whether or not to employ concentrators is an engineering decision that rests on a number of complex factors that cannot be resolved here. Either approach will lead to the required data.

E. USING MAGNIFIERS

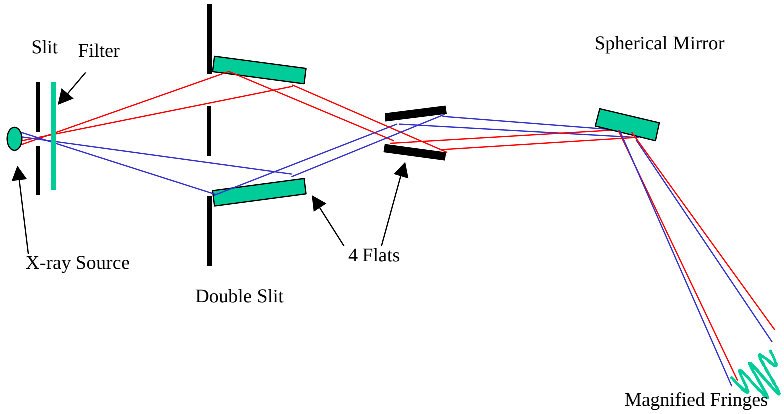

Figure 3.17: It is possible to insert a grazing optic in the converging beams and magnify the fringes. We have demonstrated this in the visible.

The distance from converger to detector can also be reduced by crossing the beams at a larger angle, reducing the fringe spacing. With high resolution detectors (i.e. small pixels) we can at least partially compensate for the close fringes. However, we can also employ a standard optical technique, which is to optically magnify the fringes from the converging beam as shown schematically in Figure 3.17. It is not immediately clear whether or not this will work. However, we have performed experiments in the visible that verify this technique works. Thus, we can add the fringe magnifier to the list of useful optical tools in the overall design.

It must be noted, however, that if the beams cross at a lower angle to create smaller fringes, the number of fringes increases, potentially violating the ability of the detector to separate the chromatic effects at the edge of the field of view.

F. TOLERANCE ANALYSIS

The tolerance analysis is surprisingly simple. In figure 3.18 we show the geometry of a wavefront on a flat mirror at grazing incidence. The idea is to keep the paths from the source at infinity to the detector the same to within a quarter of a wavelength along the emerging beam.

In the figure we derive the pathlength difference and set a tolerance limit on the motion of the mirror surface. The formulae reflect the same 1/theta forgiveness that we find in conventional grazing optics. In particular, the separation of the two mirrors must be held to $\lambda/8\sin\theta$ if the fringe position is to be held to one part in 4. From this formula emerge most of the other tolerances in the system as well.

The quality of the mirror is similarly related to the formula, as no part of the surface can exceed $\lambda/20\sin\theta$ deviation from the nominal. At 1nm and 2 degree graze this amounts to 3.6nm. This corresponds to what would be called a $\lambda/175$ mirror – very high quality but

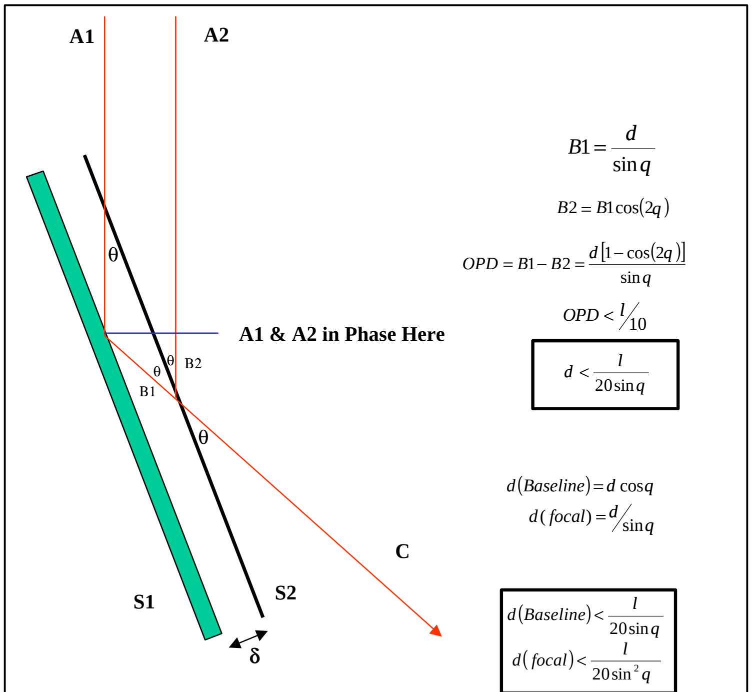

Figure 3.18: Geometry of a surface or positioning error in a grazing incidence optic.

The errors are also well within the state-of-the-art. Flats and spheres can be made to this tolerance. Even aspheres can be made to this tolerance. However, the extreme aspheres of Wolter telescopes cannot, at present, be made this well. This is another reason that the use of flat mirrors appears attractive.

Table 3-1. X-ray Interferometer Tolerances

Resolution Arcseconds	1	0.1	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
Mirror Length (m)	0.1	0.1	0.3	3	3	3	3	3
Position Stability (nm)	200	20	2	2	2	2	2	2
Angular Stability (arcsec)	50	10	2	0.3	0.1	0.01	10^{-3}	10^{-4}
Figure	λ/5	λ/20	λ/50	λ/100	λ/100	λ/100	λ/100	λ/100
Polish (Å rms)	50	30	20	20	20	20	20	20
Baseline (m)					1	10	100	1000
Angular Knowledge (as)	0.3	0.03	3×10^{-3}	3×10^{-4}	3×10^{-5}	3×10^{-6}	3×10^{-7}	3×10^{-8}
Position Knowledge (nm)					20	20	20	20
E/ΔE Detector					10	20	100	100

In Table 3-1 we show the specifications needed to build X-ray interferometers that function down to 10^{-7} arcseconds.

IV. Mission Concept

To make clear how all of the mission components come together, we present a mission concept. It is not meant to be in any way optimal, but instead to demonstrate how the problems of the mission can be solved in a coherent fashion.

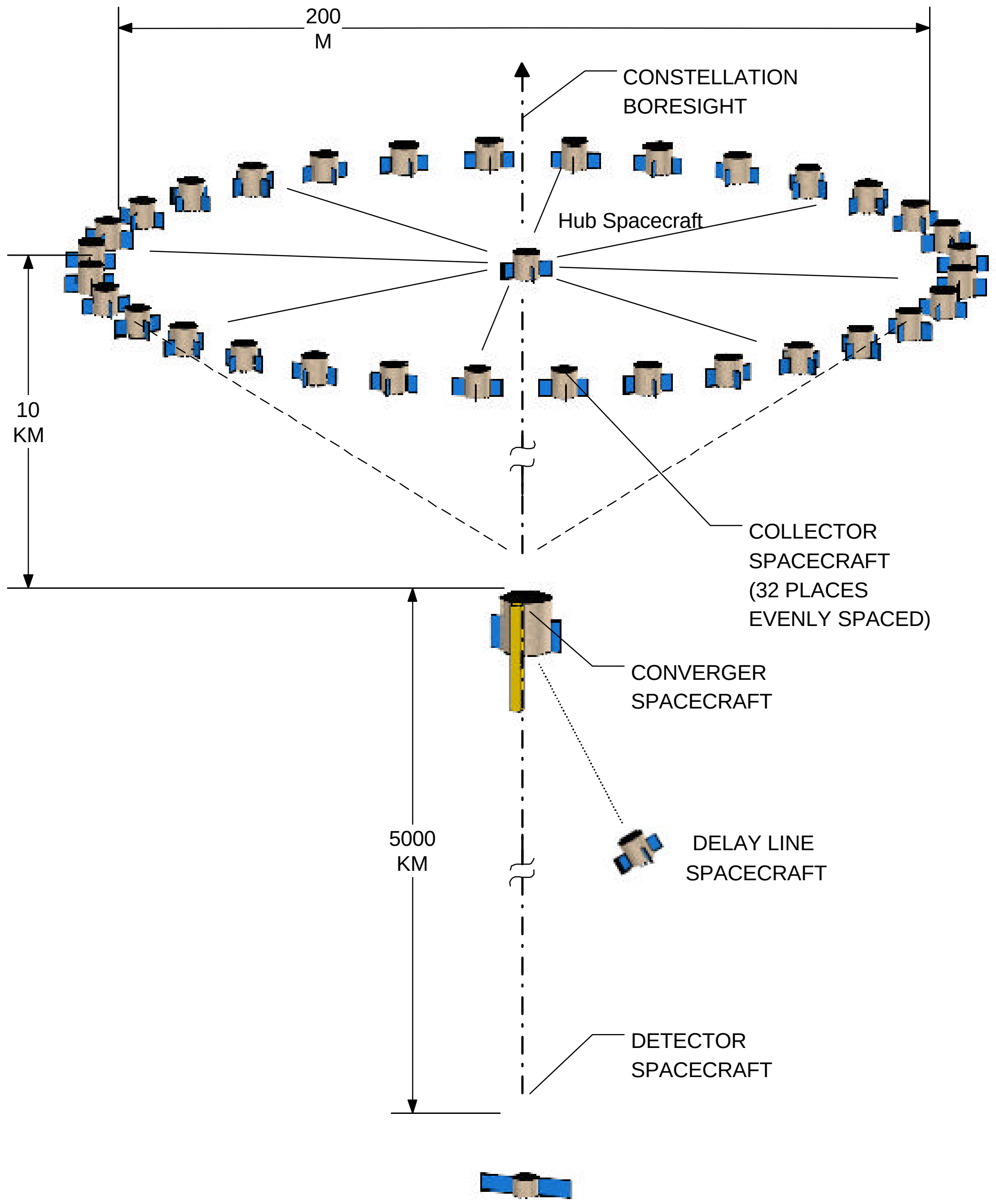

Figure 4.1: Schematic of the overall layout of the mission. The converger craft in the middle collects the radiation from 32 collector spacecraft. The hub craft, together with the delay line craft keep the system pointed to high precision.

A. OPTICAL ARRANGEMENT

The optical layout requirements drive the overall size and configuration for the mission. We have used as a baseline an array of 32 phased flat mirrors as described in section III.C. This allows us to enjoy a wide field of view and good signal to noise at the focal plane.

As we wish to observe event horizons and other extremely small targets, the baseline must be in excess of 100m. At these baselines it is impractical to build stable structures, so we need to place the individual flat mirrors on separate spacecraft, and hold their positions to optical tolerance. Thus, we envision an assembly of spacecraft as in Figure 4.1. Each of the collector craft in the assembly contains a flat mirror that is directing light from the target onto the converger. Within the converger craft is an array of flats that redirects the beam toward the detector spacecraft.

Since the system uses flat mirrors, there is no focal constraint between the mirrors in the collector spacecraft and the mirrors in the converger. Thus, flying the collectors out onto a larger circle, farther in front of the converger, can increase the baseline. The converger and detector do not change. The resolution rises.

B. DETECTOR

The choice of detector for the mission is limited. We need good energy sensitivity if we are to be able to detect fringes more than a few away from the central null. This requires that the detector be either a CCD or an imaging Quantum Calorimeter (QC).

The CCD has several advantages. First, it is a well established technology with a good track record in space. Second, it is a simple technology, not requiring fancy cryogenics. On the other hand, the energy resolution is marginal to the task at hand. For example, at 1kev, a CCD can generate $E/\delta E$ of about 20. We cannot allow the interference lines to be blurred by more than one quarter, or the image suffers badly. This implies that the maximum number of fringes across the field of view should be $E/2\delta E$ or 10 for the CCD and there will be at most 20 resolution elements across the full field of view. This is significantly less than we wish to achieve. Use of the phased array of flats can mitigate this by forcing the fringes further apart.

The QC, however, can have resolution as high as $E/\delta E$ of 1000. This allows the field of view to be as high as 1000x1000 without even requiring the effects of a phased array. At 1000x1000, the image is so large that most sources are insufficiently bright to provide adequate signal across such a large format.

C. ASPECT

Controlling the pointing of the array is without doubt, the most subtle aspect of the formation array design. We propose the following solution, but suspect that more efficient approaches exist.

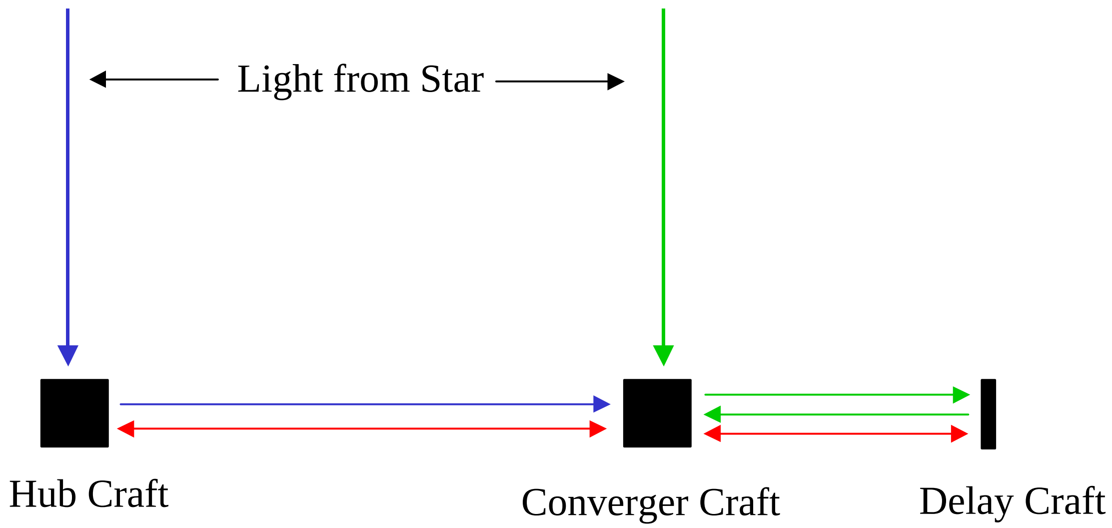

Figure 4.2: The hub craft and the converger craft together function as a stellar interferometer to gather the information needed for ultra-high precision stability pointing. The delay craft is needed to equalize the path lengths for the two optical paths.

We start by placing a spacecraft at the hub of the 32 collector craft. It will become the reference point which the collector craft will use to maintain position. The hub position that the craft must find and maintain is on the line that stretches from the center of the converger mirrors to the target in the sky.

Two stars, each close to perpendicular to the line of sight to the target, and nearly perpendicular to each other are chosen. In Figure 4.2 we show the wavefront approaching the hub craft and the converger craft which, together, form an interferometer. The light impinging on the hub craft is reflected through 90 degrees and sent to the converger. Thus, by the time it reaches the converger, it has traveled farther than the (green) beam that reaches the converger. The light that strikes the converger is then sent to a delay line spacecraft that equalizes the path lengths and allows a null interferometer to be built in the converger. The distance between the converger and the hub, and between the converger and the delay craft must be monitored by laser beam and stabilized with formation flying. Then, if the craft fall off the target line, a shift in the null will be recorded.

Unfortunately, both pitch and yaw need maintenance. This requires that the process be simultaneously maintained on two stars. Since the stars cannot be perfectly placed, the delay line length will have to be different. Thus, it may be necessary to have two delay line craft. The good news is that the delay line craft can be very similar in size and performance to the collector craft, so the addition of two more craft to the fleet does constitute a major increase in mission complexity.

D. FORMATION FLYING

Once the hub craft is firmly fixed along the line of sight to the target, it may be used to maintain the position and separation of the collector craft. Each collector craft then directly monitors and maintains its distance to the hub. This is the most sensitive

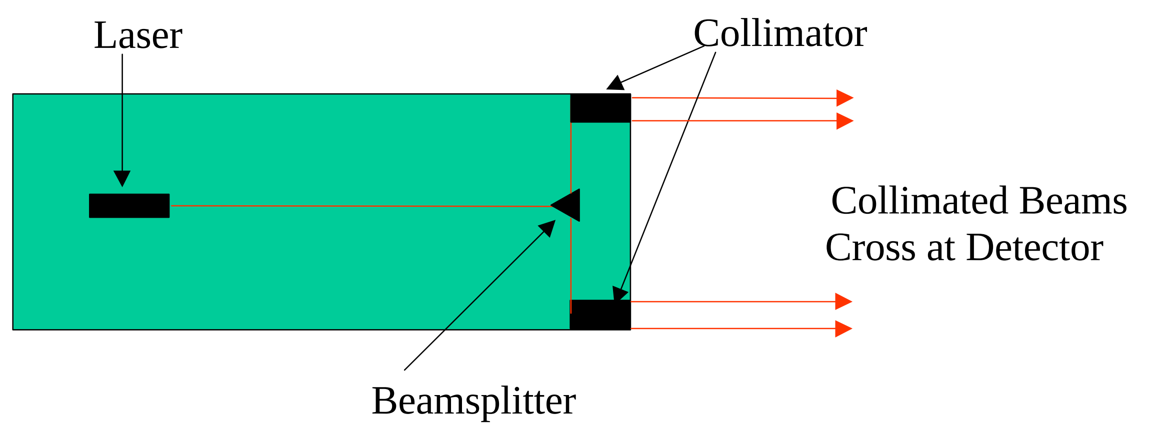

Figure 4.3: The light from the laser is split and sent through parallel collimators.

direction, requiring stability of about 1nm. Simultaneously, each craft must maintain its distance from the converger craft, although at a looser tolerance. The separation between the craft must also be maintained, but this also is more relaxed.

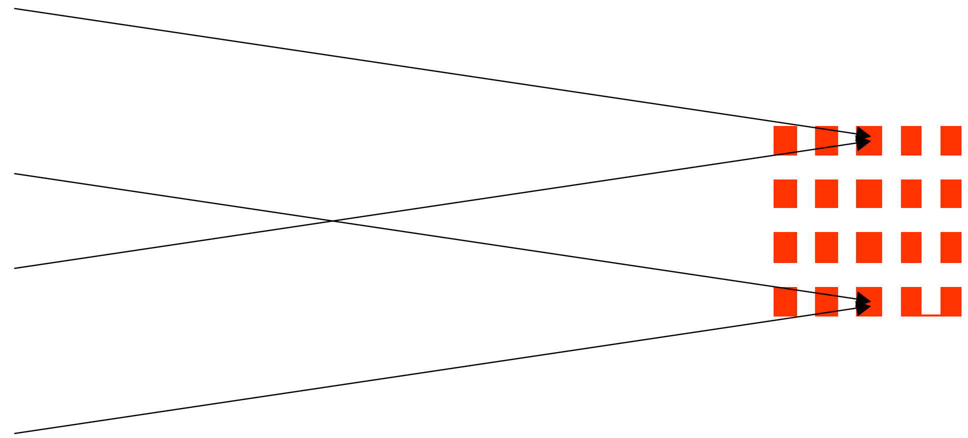
Figure 4.4: When the beams from the four collimators cross, the create a fringe pattern that can be used to provide the necessary information for holding the detector craft in the correct position.

The position of the detector is a bit tricky too. Its distance from the converger, though large, is not a sensitive parameter. We can handle this by creating an interference pattern from the back of the converger craft. We show in Figure 4.3 a laser beam on the converger craft that is split and then passed through four collimators. When the nearly parallel beams cross at the distance detector craft, as in Figure 4.4, they create a fixed interferometric pattern that the detector craft can use to slave its position to the optic axis of the converger.

E. SPACECRAFT

On the whole, the individual craft are not particularly fancy. They carry retro-reflectors, stabilizing gyros and lasers, but their overall structures, power requirements and data requirements are modest.

The aspects of the spacecraft that are challenging are discussed in the next section.

V. Technical Challenges

A. FORMATION FLYING

To minimize disturbances, the constellation of spacecraft operates in a heliocentric driftaway orbit with a semimajor axis of 1 Au and an ecliptic inclination of zero. To minimize thermal stresses on the S/C, the constellation boresight is always oriented at right angles to the sunline, although it is free to rotate 360 degrees around it.

In operation, the Converger, by far the most massive of the S/C operates in the orbit plane at all times to minimize the constellation's propellant consumption. Depending on the orientation of the constellation boresight about the sunline, the collector S/C position will be in a range from 0 to 10 km from the ecliptic plane. The lightest S/C, the detector, will operate in a range of from 0 to 5000 km from the plane.

To keep the S/C in their correct positions to this level of accuracy for all possible constellation boresight orientations, they must be continuously stationkept against forces exerted by solar radiation pressure and solar gravity.

Solar radiation exerts a constant pressure on the order of 5 to 9 E-6 N/M2 at 1 Au on each S/C in the constellation. The exact value will depend on the reflectance of the S/C. the pressure will be constant, as each S/C's attitude with resect to the sun is constant for all allowed boresight orientations. Solar radiation pressure disturbances will be minimized by equalizing the "ballistic Coefficient" or area mass loading of each of the constellation's S/C elements, using light weight solar sails if necessary. This approach will keep the magnitude of solar disturbances small compared to the solar gravitational forces, allowing the stationkeeping system to be designed to compensate for solar gravity effects alone.

Solar gravity exerts forces on the Collector and Detector S/C as they operate in "non-Keplarian" orbits. The more massive Converger S/C is force free, as it alone is in a true Keplarian orbit at 1 Au radius and always in the ecliptic plane.

Gravitational forces are maximum for the detector S/C when the constellation boresight is normal to the ecliptic plane, elevating (or depressing) the S/C by 5000 km above or below the plane. This imparts a constant acceleration on the order of 2 E-7 m/s2 in a direction perpendicular to the ecliptic plane (PEP) to the detector S/C. If uncompensated; this acceleration would relocate the S/C by about 750 m/day. For the same constellation orientation, the Collector S/C, operated on by acceleration forces two orders of magnitude lower, would be displaced by about 1.5 m/day.

For a Nominal 1000 kg Detector S/C, compensating this gravitational acceleration would require a continuous force of about 198 μN. The force required to provide an equivalent force compensation for the collector S/C is on the order of 1 to 2 μN. Nominally, these forces act along the constellation boresight. However, the need also exists to compensate for second order forces (such as minor differences in ballistic coefficient, or the gravity of earth or Jupiter) which even though lower in magnitude by two or three orders of magnitude are effectively omnidirectional, and over many days or weeks can induce many meters of displacement.

The full range of these requirements could be met for the collector S/C by providing for a continuous force on the S/C of 0 to 0.5 μN in each or 3 axes. The total worst-case impulse delivered to the S/C using this approach is about 12.6 N-s per year, or 126 N-s per axis over 10 years.

The equivalent pulse plasma thruster (PPT) complement for the detector S/C would require the same force and total impulse level for the two axes transverse to the constellation boresight. Along the boresight axis, however, up to 100 μN thrust and 3154 N-s of impulse per year will be required, for a total of 31,540 N-s for 10 years.

2) Notional Stationkeeping Approach: While many approaches can meet these requirements, a notional approach using flight proven PPTs can meet the requirements described with minimum system impact while providing a minimum ten year mission life with margin.

Each of the collector S/C will be equipped with 6 to 8 PPT's each of which thrusts through or along an axis parallel to one that passes though the S/C CG. The thrusters are located to provide 3-axis translation of the vehicle without inducing moments.

All three of the Collector S/C axes, and the transverse axes of the detector S/C, are equipped with 17 μN PPT units of the type used on the DOD LES-6 mission. These thrusters operate at an Isp of 300 s, operate on 6 W of power, and have a total impulse capability of 320N-s, providing a lifetime of > 10 years with over 100 % margin when compared to the 126 N-s requirement.

Thrusters for the boresight axis of the detector S/C will be larger units or the type used for the DOD LES 8/9 mission, which weigh 6.6 kg each, and feature a thrust level of 300 μN and an Isp of 1000 s. These units require 25 W, and provide a total impulse of 9940 N-s each. Four of these units will provide a total of 33,600 N-s, yielding a margin of 26% over the 10-year requirement. The thrusters would be used in pairs, with two burning at a time to limit power consumption to 50W. Alternatively, new PPT thrusters with a higher total impulse capability could be developed.

B. ASPECT CONTROL

1) Aspect Control Requirements: Between observations, the MAXIM constellation must slew between targets. The following requirements and groundrules were adapted to guide definition of the slew approach:

- The Converger S/C is equipped with order 10m pitch and yaw interferometers with 4 microarcsec resolution to lay the constellation boresight
- Collector and Detector S/C pointing control uses Converger attitude knowledge plus metrology
- All S/C equipped with 20 arcsec class ADCS for setup of metrology chain after slew

- All S/C equipped with 5 m class autonav for setup of metrology chain
- Constellation boresight axis always perpendicular to sunline
- All boresight slew maneuvers are around sunline
- Constellation Boresight re-orientation rate 5 deg/day max
- Constellation roll attitude (about boresight axis) controlled to allow for collector metrology sun avoidance of 10 deg max
- Constellation Roll attitude maneuver for collector metrology sun avoidance on 5 day centers
- Aspect re-orientation maneuvers are point-to point
- No X-ray interferometry during re-orientation maneuvers
- 6 hour "constellation re-build" after each aspect maneuver to achieve full metrology accuracy

2) Notional Aspect Control Approach: Figure 5.1 shows a schematic view of a typical constellation slew maneuver. The entire constellation pivots about the CG of the massive Converger S/C, forcing the ring of collector S/C and the single Detector S/C to translate to their new positions. All translations are “point-to-point” along the shortest path to minimize propellant consumption. To further minimize propellant usage, all translations use a boost-coast-deboost trajectory, where the S/C is accelerated to a fixed velocity chosen to achieve the required translation in the designated time, coasts for the bulk of the translation period, and then decelerates to come to rest in its new position.

Inspection of the figure shows that the translation required by the detector S/C is four orders of magnitude greater than that of the Collector S/C (436 km compared to 9m) because of the Detector S/C’s 5000 kg “lever arm”. The required translation for the Collector S/C can easily be handled by the PPT thrusters used for stationkeeping, at a propellant consumption per S/C of about 0.03 g for a five-degree re-orientation.

Accordingly, the challenge in aspect control becomes that of translating the detector S/C 436 km in one day (for a 5-degree boresight slew). In our notional approach, this is accomplished by thrust from a 0.2 N hydrazine arcjet, of the type currently used for GEO Comsat N-S stationkeeping. This unit features an Isp of 600s, requires about 2 kW of electrical power, and has a dry mass of less than 22 kg for two thrusters.

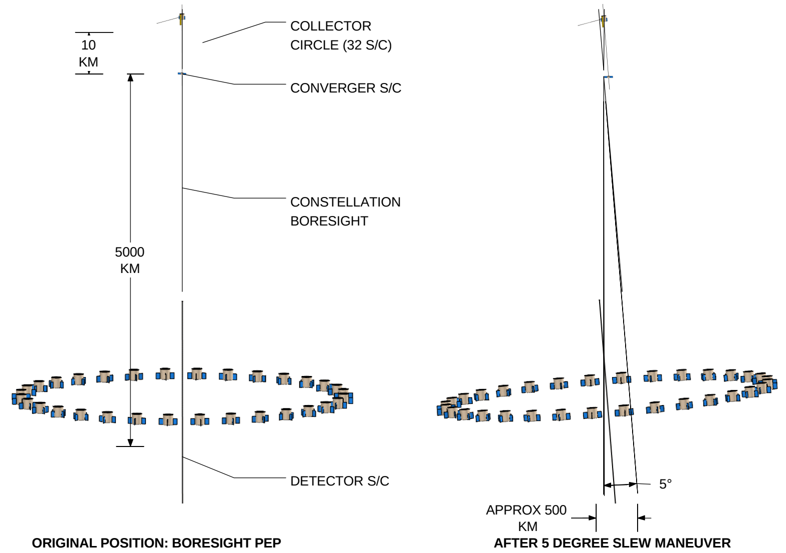

Figure 5.1: Five degree slew maneuver.

In operation, when a boresight slew is required, the arcjet is fired for about three and a half hours to accelerate the collector S/C to a velocity of 5 m/s (18 km/hr). This is sufficient to cover the required 436 km in one day. As the final position is approached, a second arcjet fires for 3.5 hr to bring the S/C to rest. The low rate of acceleration has been chosen to minimize the thrust level, and electrical power demand, of the arcjet. The arcjet was chosen as opposed to hydrazine thrusters because of its 600-s specific impulse, which consumes only 900 g of hydrazine for the 5-degree re-orientation. A hydrazine monopropellant approach would use almost 3 kg of hydrazine for the same translation.

3) Aspect Control Limits: Given the baseline constellation separation of 5000 km, then for small boresight slew angles, and a 1 day slew duration, the propellant burn per slew is proportional to the slew angle, yielding a propellant consumption of about 180 g per degree for the baseline arcjet thrusters.

If we assume an optimal observational strategy for the constellation which limits slews to an average of 1 degree/day, annual propellant consumption will be 66kg, or 660 kg for 10 years. This is well beyond the lifetime propellant thruput limit of existing arcjets (about 180 kg). This is a definite limit.

Extension of the constellation converger to detector distance will increase the propellant consumption in direct proportion to the increase in distance. Even for the increased efficiency propulsion systems described below, this will probably limit practical converger to detector distance increases to a factor of two at most.

A number of alternative, higher specific impulse propulsion approaches exist, among them ion, magneto plasma dynamic, and stationary plasma thrusters. Each potentially offers a factor of four or better reduction in propellant consumption, at the price of an equivalent increase in power draw. A detailed trade study will be required to define

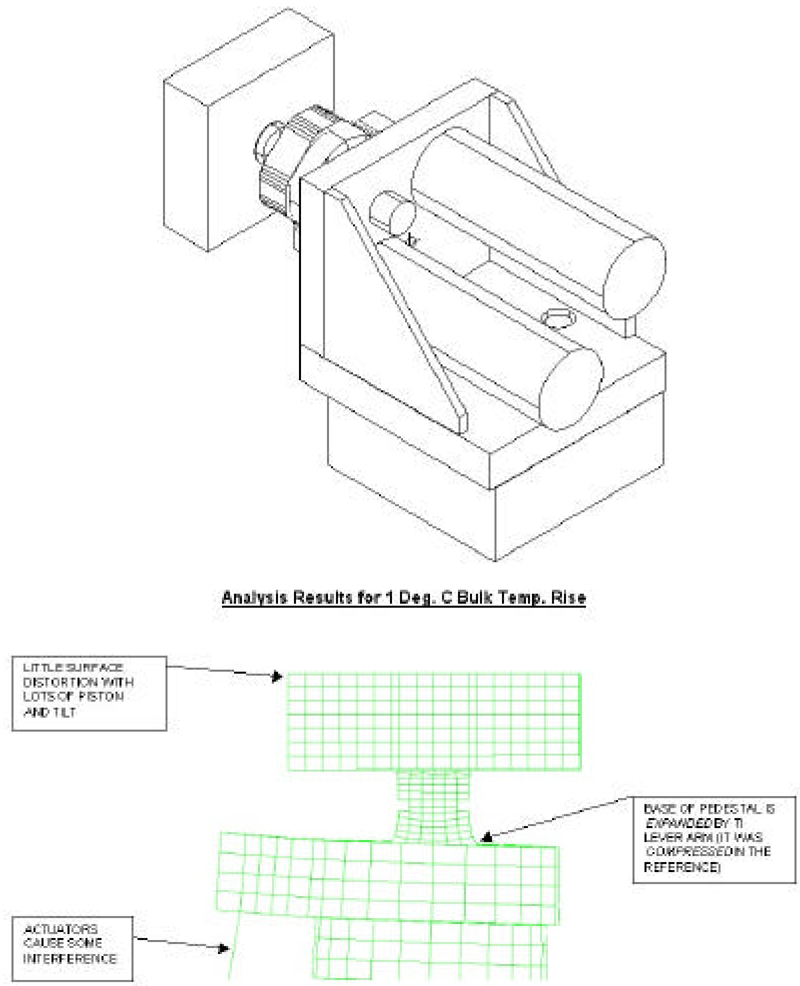

Figure 5.2: Finite element analysis of a low stress mount for mirrors has been started.

which of these options provides the best combination of cost and performance for the operational MAXIM constellation.

C. MIRRORS, MOUNTS, ALIGNMENT AND THERMAL

The interferometer's active area requirement and proposed instrument configuration drive the mirror geometry to a long narrow shape. This represents a challenging mirror shape to mount even with relatively loose surface figure requirements. Current tolerance studies indicate each mirror's surface accuracy will be required to meet $\lambda/100$ rms surface figure with less than 5Å surface roughness. Such an accurate surface figure requirement makes many subtle errors significant in estimating the total wavefront error. An acceptable mounted mirror's $\lambda/100$ surface must include errors due to alignment, thermal gradient, jitter, stability, assembly, manufacturing, test, 1g release, temperature

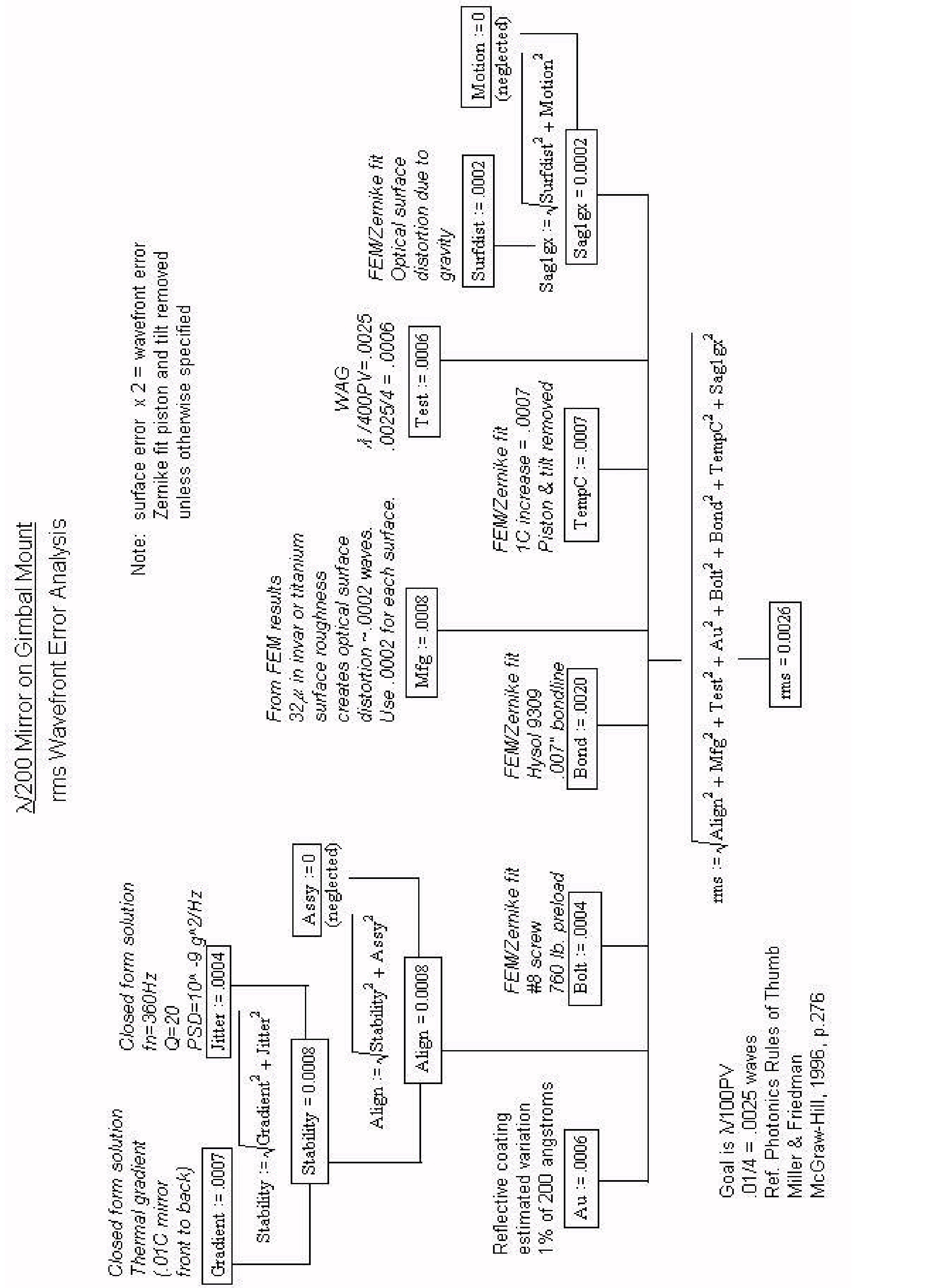

Figure 5.3: Mounting of high quality mirror mount is a necessary step to launching the mission. Analysis is already underway.

coating thickness variation. We can guess which errors will have the greatest effect on a mirror of this size and shape, however we have chosen to solve this problem in stages. Investigating a smaller mirror mount with similar requirements has given us the ability to quantify the errors and environmental effects most likely to become drivers that will require technology development. This approach allows us to break down the problem into smaller parts to identify areas that require technological advancement uncoupled from the known challenge involved with the mirror's size and shape. Additionally, we have completed the analysis for a smaller system that can be built and tested in a scaled down model of the interferometer. Such tests will be imperative to identifying real-time alignment, thermal, imaging, vibration/jitter, and other unknown subtleties requiring early attention that may not be apparent through analyses.

The analysis of a smaller mirror mount with similar requirements and analytical results indicate a $\lambda/400$ rms ($\lambda/100$ PV) surface figure is reasonably attainable for a 50mm square mirror made of fused silica. Wavefront error analysis based on those analytical results suggest the most challenging factors include: thermal gradient, and piston and tilt error associated with a bulk temperature increase (optical surface distortion is reasonable). The estimated allowable thermal gradient between the front and back of a mirror may be less than 0.01°C. The piston and tilt error of the mirror associated with a change in the stabilized temperature will probably drive the allowable time length of an observation. The mirror positions will need to be corrected between observations to

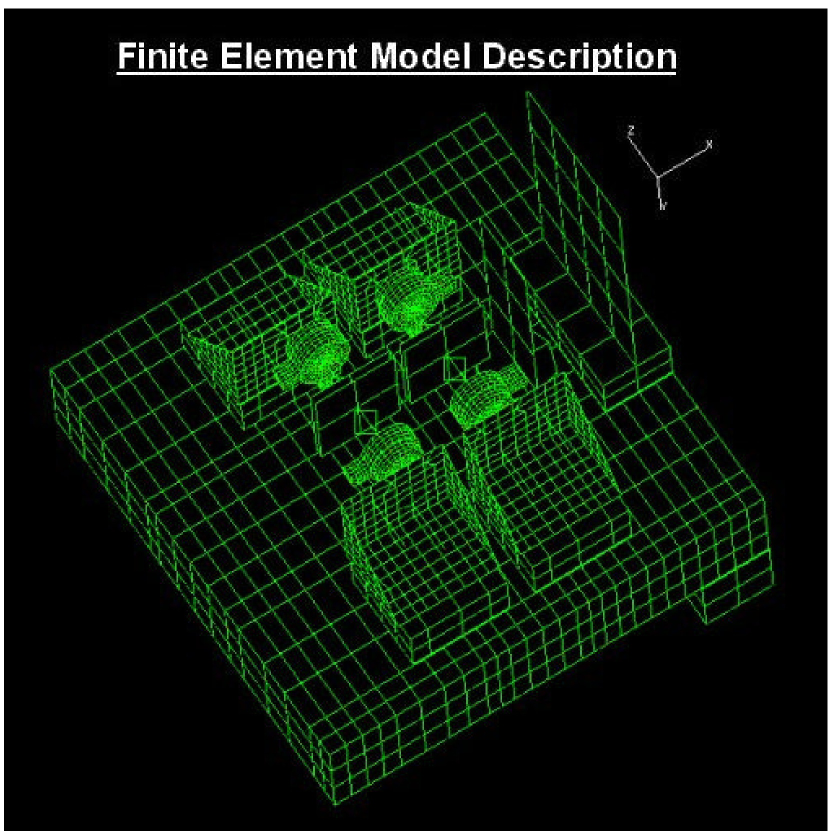

Figure 5.4: Assembly of mirrors in arrays is also being studied.

maintain equal pathlengths. The mirror substrate thermal gradient will be difficult to maintain because heat emitted by motors used to manipulate the mirror position will make temperature difficult to stabilize. Materials with improved thermal properties could make this problem more easily contained in the future. Motors capable of high-resolution, stability, and position knowledge that emit very little heat would also help.

The long narrow mirrors will have the same thermal challenges at a much greater magnitude. A challenging parameter for a small mirror certainly indicates an imperative need for technological advancement to support similar requirements in a much larger mirror. Other factors we expect to be difficult are gravity release, stability due to jitter (a function of the mirror's fundamental frequency and mode shape), and the ability to test the mounted mirror's surface figure. The mirror size and high surface accuracy require a test apparatus beyond standard laser interferogram capability.

Gravity release and jitter stability of a mounted mirror may require the development of a stiffer material with lower mass, good stability over time, and of course a lower thermal coefficient of expansion. Current materials used for high quality optics have good thermal and mechanical stability, however, these materials also tend to be brittle, prone to fracture, and mass can be prohibitive for large optics. Traditional optic fabrication methods are well suited for symmetrical optics made of traditional materials. We plan to analyze the mirror mount configurations employing existing optical materials. Traditional materials such as Zerudor, ULE, and fused silica may be viable candidates with the advent of thermal technological advancement. New methods of fabrication and polishing may also be required to support a design using traditional materials. Two possible avenues are active self-aligning optics and segmented mirror sections (up to seven meters long) making up one long narrow mirror. New hybrid materials may be necessary to achieve the next level of accuracy and size in space-borne optics.

Active alignment of the optics on-orbit will be critical to maintaining such ambitious resolving power. Our studies using a single channel instrument consisting of four small mirrors have uncovered alignment issues that will apply to each channel of the instrument. Every mirror in the interferometer will require on-orbit motion in three degrees of freedom (tip, tilt, and piston). Current tolerance studies indicate optic alignment in the remaining three degrees of freedom may withstand launch. Attaining equal pathlengths in each channel will require tilt and piston control of each mirror at an estimated 10 nanometer resolution and knowledge. Equalizing pathlengths in numerous channels simultaneously while providing positional stability over the length of an observation may certainly be considered challenging. Developing continuous on-orbit automated sensing and correction to maintain equal pathlengths in each channel of the interferometer simultaneously could eliminate or greatly reduce these effects. The advent of this capability at the nanometer level would provide incredible imaging capability.

Thermal stability requirements will be a function of the length of time during which each channel's pathlengths may not be optimized. This time constraint may lend itself to the time length of an observation. Continuous automated sensing and pathlength correction could loosen some of these thermal requirements making longer observation sessions a reality. Investigating this avenue as part of the system analysis would be beneficial. A clever mirror mount may minimize wavefront error due to thermal changes, but still cause tip, tilt and piston motions that will far exceed allowable tolerances. Once again this thermal issue may be mitigated with the advent of automated alignment corrections. The thermal challenges are significant, but appear to be integrally tied with mirror, mount, and alignment solutions.

D. CALIBRATION

It may not be possible to fully calibrate the instrument on the ground. The longest vacuum tank we have available is the XRCF at MSFC, which is 500m. Resolution of one micro-arcsecond at that distance represents a size scale of 2.5nm. We cannot currently even create mask features this fine. We may have to check components, and then perform an in-orbit checkout.

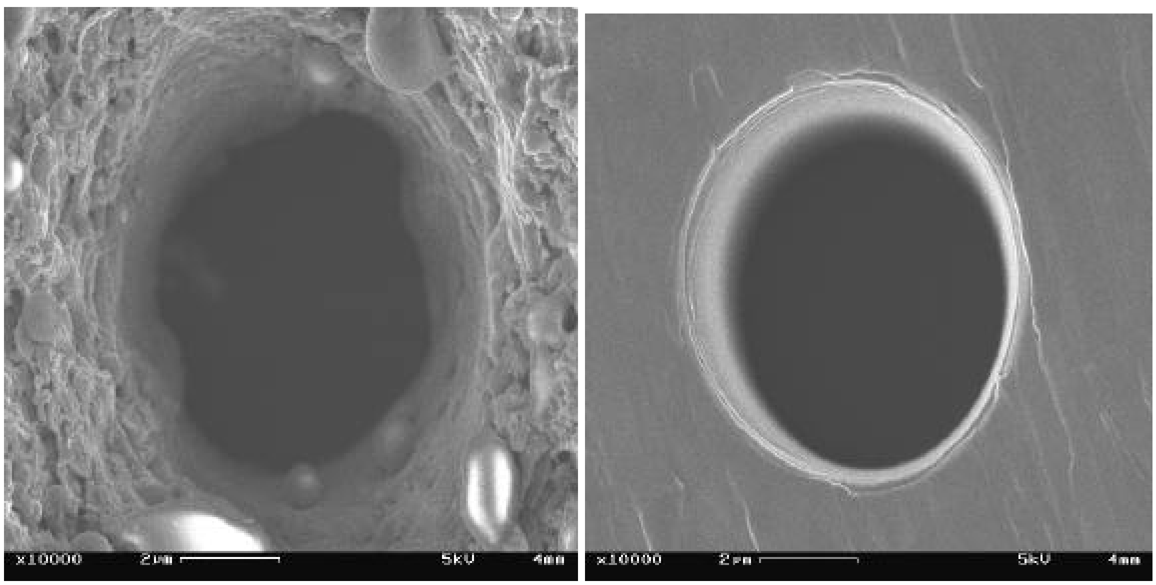

Figure 5.5: To the left, a 5 micron hole was drilled in moly sheet using a laser. To the right focussed ion beam was used. It is clear that the focussed ion beam has excellent potential for the creation of very fine calibration targets.

For the development and testing phase of the mission a critical task is to fabricate high-quality target apertures designed to test the diffraction-limited performance of the optical system. The idea is to use microscope optics to image backlit apertures onto the detector. Target apertures of various shapes are useful, such as holes, slits, cross and wagonwheel patterns, and gratings. In order to fully test the optical system, apertures need to be cut into thin, x-ray opaque foils, and need to have sub-micron feature sizes with sharp edges and corners. Specialized laboratory facilities are required to fabricate targets of this quality. Figure 5.5 shows a recent advance in our ability to make better calibration masks.

E. IMAGE RECONSTRUCTION

Image reconstruction is accomplished in computers on the ground in exactly the fashion that radio interferometers create images. We do not expect any serious problems in this area. Image reconstruction is a standard procedure in the x-ray, most notably used in rotation modulation collimators and in CT scans. However, handling the details will require some software development.

We need to build a software model and start developing and evaluating algorithms that will quickly and effectively create images from the data stream from an x-ray interferometer.

VI. Mission Limitations

In this section we discuss the eventual limitation of the technique in terms of increased resolution. Since the primary mirrors can be flown farther apart to create a longer baseline, the resolution can rise. What limits the practical resolution? We have looked at several important parameters as the size of the primary array grows.

In summary we find that the limit is likely to be aspect information coming from deep space. None of the other effects becomes severe until the baseline of the x-ray interferometer is around 100,000km, with a resolution of 10^{-17} radians. But, most stars have sufficiently low surface brightness in the visible that we either cannot detect them or they become resolved across a baseline of about 100km. Use of non-thermal visible sources or use of an x-ray interferometer may be needed if we wish to push below 10^{-13} radians.

A. STATIONKEEPING

The stationkeeping approach described using existing technology can provide at least a 20 year life for all requirements except along-boresight control for the Detector S/C. The baseline 20 year life could be doubled by simply adding a second set of thrusters to each axis. Accordingly, these requirements are not considered limiting.

Limits are completely dominated by Detector S/C along-boresight control. For equivalent lifetime, total impulse requirements are a linear function of the distance along the boresight; a 10,000 km distance would require twice the total impulse or reduction of the mission lifetime to 5 years. Removing these limits could be accomplished by adding more PPT's, or by using a higher specific impulse propulsion approach such as ion or magneto-plasma-dynamic thrusters. A detailed trade study would be required to determine the optimum approach. In any case, an absolute limit imposed by propellant load would probably be reached at between 50,000 and 100,000 km separation.

B. POSITIONAL INFORMATION

Our positional information must be maintained by monitoring the stability between the primary mirrors and the hub craft. While we have not yet directly worked on the design for such a system, it would probably resemble the separation monitoring system under development for the LISA mission. LISA claims that through use of laser beams fed through a telescope (collimator), that the separation can be monitored to better than a nanometer over a million kilometers.

C. ASPECT INFORMATION

We expect to obtain aspect information by using a Michelson flat at the hub spacecraft to redirect the signal from a stellar object into an interferometer on the converger craft. As the array flies apart, the baseline of this interferometer grows along with the baseline of the x-ray interferometer. Two effects can limit the effectiveness of this aspect interferometer.

First is the diffraction from the Michelson flat. A ten meter optic will cause visible light to diffract one part in $2x10^7$. If the beam is to diffract to less than 100m across, resulting in a factor of 100 loss in signal, then the baseline of the aspect interferometer can be as high as 2 million kilometers. This indicates an x-ray interferometer with a baseline of 200,000km and resolution of 10^{-17} radians.

The other effect is the size of the star being used to provide the reference wavefront. We rapidly start to run out of thermal reference information in the visible portion of the spectrum. We can use main sequence stars at a distance as great as 10,000pc, which have an angular extent of around 10^{-11} radians, which will be resolved across a baseline of 100km. We could use white dwarf stars, but, while they are smaller, they are also dimmer, and we cannot see them a great distances. Similarly, the visible emission of AGN's is too extended. This problem is a direct result of the relative faintness of visible emission from objects. The only hope to solve this problem in the visible is to observe non-thermal objects such as pulsars. The Crab pulsar is detectable in the visible, yet is only a few kilometers across, so might give us the needed information. At a diameter of 10km at 2kpc, it has an angular extent of 10^{-16} radians, a reasonable match to the x-ray resolution.

Of course, we can solve the problem by getting our aspect information from an x-ray interferometer. However, it will take some additional work to determine if this is practical.

D. DIFFRACTION OF BEAM

The x-ray beam itself will diffract as it travels from the primaries to the converger spacecraft. If the beam spreads too far, the signal will be lost, and the sources will become unobservable.

As the baseline B is about one tenth of the distance to the converger, and that mirrors have an effective aperture of d. If the beam must spread to no more than 10d, then we find that the limit is encountered when:

$$\left(\frac{l}{d}\right)10B = 10d$$

using 10cm for d and 1nm for λ we can solve for B. We find that the baselines in excess of about 10,000km will start to have severe losses due to diffraction. However, B rises as the square of d, so if we build unusually large mirrors, or phase smaller mirrors within each spacecraft, we can raise the baseline quickly. Baselines in excess of 1,000,000km become acceptable.

E. BRIGHTNESS OF TARGETS

Figure 1.1 has already addressed this problem. We find that a blackbody with a surface temperature of 10^7K will generate sufficient signal that a resolution of 10^{-15} arcseconds can be recorded. Also shown on the graph is that the baseline needed to achieve this resolution is 10^8km, close to an AU.

VII. Moving Forward

Within the limitations of a Phase I study we have tried to identify and quantify the problems facing the realization of x-ray interferometry as a mission. In Phase II we will try to further improve the confidence that NASA can place in the technical concept.

A. DETAILED MISSION DESIGN

The next step is clearly to create a detailed mission design. While we currently have a strawman design and first cut estimates of the difficulties and problems to be faced, a detailed design effort, utilizing experts in all the various disciplines of space engineering will be needed to find an optimal solution to the problem.

B. DEVELOPMENT OF KEY TECHNOLOGIES

Several technologies are key to the acceptance of the mission concept. These include:

a) fabrication and mounting of large, high quality mirrors,
b) formation flying of multiple spacecraft, including creation of the array, bringing the mirrors into phase and them holding them during the observation,
c) creation and maintenance of the information needed to hold the formation in position.
d) Monitoring of celestial sources to high precision across large distances between separate spacecraft.

During Phase II we expect to further investigate these key technologies and decrease the technical risk associated with each of these.

C. COMMUNITY ACCEPTANCE

The science community, like most human communities, is often reluctant to embrace a new ideas and supplant older ones. There is a continuing feeling within the astronomy community that x-ray interferometry is impractical. We have noticed that there tend to be two origins for this feeling. First, many feel that x-ray sources are too faint to support high resolution imaging. This, of course, is dead wrong. The second problem is the perception that x-ray optics are crude and impossibly difficult to build. There is some truth to this, but proper technical development can change this.

We need to keep making the case to NASA and the science community that x-ray interferometry is practical and will return revolutionary science. This will require continuing to keep the science and technology high profile.