X-ray Interferometry
Ultimate Astronomical Imaging

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Technical Section

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ABSTRACT

The x-ray band of the spectrum is the natural band for ultra-high resolution imaging. The sources have high surface brightness, the features are unusually compact, and the short wavelengths allow high resolution in relatively small instruments. In Phase I we reviewed the scientific potential of x-ray interferometry and showed how spatial resolution a billion times finer than HST’s can be achieved in the foreseeable future. That extraordinary improvement in resolution will enable new probes of extreme environments like the warped space-time regions above the event horizons of black holes. We present an instrument design concept for the observatory, set the mission requirements and tabulate the instrument tolerances. We have studied the component technologies that are needed to assemble a full mission. We have uncovered the limitations on the eventual spatial resolution and show how the system can function down to a nano-arcsecond and below. It is our purpose to make a convincing case to both NASA and the science community that this advanced concept is of use in future missions. With the additional study proposed for Phase II it should be possible to fully demonstrate a reliable technical pathway to the launch of an exciting new class of scientific mission.

I. CONCEPT DESCRIPTION

A. THE POTENTIAL OF X-RAY INTERFEROMETRY

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.
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.

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

\[ B_\nu = 1.8 \times 10^{-5} T^4 \text{ erg/cm}^2/\text{s/ster}. \]

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 ($\theta_{\text{min}}$), 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 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 $1.7 \times 10^{-15}$ radians in extent, or $7.6 \times 10^{10}$ cm, about the radius of the Sun. However, in the X-ray, the angular limit would be $5 \times 10^{-20}$ 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.

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.

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

Figure 1: A 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.
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:

\[
R = \frac{\lambda}{36000D}
\]

where \( \lambda \) 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 a fashion that does not compromise 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 2x108Å on a baseline of 107m 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 Phase I 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.

For starters, at one milli-second and just below, we will be able to image the coronae of nearby stars. Consider being able to watch plasma stream between the components of a close binary star as imagined in Figure 2.

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.

Figure 2: Artist’s conception of the shared corona of a close binary star as imaged by an interferometer in the x-ray.
An entirely unexpected way to study these black hole laboratories would be to take an actual picture. Such images would provide the ultimate proof of existence of these objects of the utmost gravity. They would allow us to the physics of the innermost accretion disk, the 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.

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.

B. MISSION REQUIREMENTS

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

\[ \theta = \frac{\lambda}{2B} \]

where B is the baseline.

In this Table 1 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.

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.

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.
Table 1: Targets and their Characteristic Sizes

<table>
<thead>
<tr>
<th>Target</th>
<th>Angular Size (radians)</th>
<th>Baseline at 10Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun at 1pc</td>
<td>5x10^{-8}</td>
<td>1cm</td>
</tr>
<tr>
<td>AGN Accretion Disk</td>
<td>5x10^{-10}</td>
<td>1m</td>
</tr>
<tr>
<td>AGN Event Horizon</td>
<td>5x10^{-12}</td>
<td>100m</td>
</tr>
<tr>
<td>Binary Accretion Disk</td>
<td>5x10^{-14}</td>
<td>10km</td>
</tr>
<tr>
<td>Neutron Star</td>
<td>5x10^{-16}</td>
<td>1000km</td>
</tr>
</tbody>
</table>

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.

**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.

**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.

**C. FLAT MIRROR X-RAY INTERFEROMETRY**

One of the major impediments to x-ray interferometry has been the absence of an effective beam combiner. In the visible band partially silvered mirrors are used. In the radio calibrated oscillators provide the information. However, in the x-ray only Laue crystals have ever achieved beam combination, and they are far too inefficient to be used for the faint, celestial x-ray sources.
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 4, 5, and 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 $\lambda/100$ or better (where $\lambda$ is 6328Å). This is better than the average flat mirror that 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.

Figure 4: Basic arrangement of flat mirrors at grazing incidence that creates a practical interferometer.

Figure 5: A beam mixer can be made from two grazing flats. This converger uses distance to mix the wavefronts at a low angle.

Figure 6: The fringes spacing is amplified on the detector where the two wavefronts cross.
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.

During 1999 we 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 results. The experiment has been written up and submitted to Science for publication.

Additional details may be found in the Phase I report.

The instrument is of the simple four flat mirror design shown schematically in Figure 7. The work was performed in a 120 meter long vacuum facility at the Marshall Space Flight Center. In Figure 8 we show the histogram for the signal recorded on the
instrument detector using Mg-K x-rays at 1.25keV. A two bin boxcar smooth was run across the data to suppress the Poisson noise.

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. Further work was performed in the extreme ultraviolet that verified the fringes and further advanced understanding of the device.

**Using In-Phase Flats**

An instrument 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 9. 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 only artistic, but interesting. In figure 10 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!

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.

Tolerance Analysis

Derivation of the tolerance analysis is presented in the Phase I report and is bit lengthy
for presentation here. Instead, we merely present a Table 2, which tabulates the tolerances
needed as a function of the desired spatial resolution. We see that, for the most part, the
tolerances to do not become more stringent as the baseline grows and the resolution rises.

Only the angular stability and knowledge specs grow tighter. However, if one notices
that the instrument grows is growing in size at the same rate as the angular specs grow

Figure 10: 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.
tighter, one concludes that the tolerance on the relative position of the front and back of the instrument is remaining constant. Thus, all the specs of the instrument remain constant. They just must be held across a larger distance.

This is what allows us to consider an adjustable architecture for the mission. One in which the resolution can be increased at the expense of field of view, depending on the size of the target.

### Table 2 X-ray Interferometer Tolerances

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

### D. MISSION ARCHITECTURE

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. Our first serious attempts at optimization will come in Phase II.

### 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 I.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 11. 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.

Figure 11: 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.
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.

**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/δE 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/2δE 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/δE 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.

**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.
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 12 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.

**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 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.
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 13 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.

**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.

**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.

**E. 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.

**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.

**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.

**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 $2 \times 10^7$. 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.

**Diffraction Of The 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:

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

using 10cm for $d$ and 1nm for $\lambda$ 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.

**Brightness Of Targets:** Figure 1 has already addressed this problem. We find that a blackbody with a surface temperature of 107K 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 108km, close to an AU.

**F. 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
- Ultra-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 Phase I we were 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. SUMMARY OF PHASE I

The results of the Phase I study are presented in more detail in the Final Report to NIAC that was submitted at the same time as this proposal.

As we started into Phase I, we rapidly discovered that we had insufficient expertise within our institutions to answer many of the mission design questions that kept coming to the forefront. To solve the problem we re-directed part of our funding to Ball Aerospace in the form of a small subcontract. Dennis Gallagher and Rich Reinert were then able to join the effort. Together, we were able to answer some of the most vexing questions.

We reviewed all the available options for choice of optical design. We settled on use of the x-configuration flat mirror design which we had invented and proven in the laboratory as part of a different project during 1999. The design is highly efficient and provides a versatility in observation that makes it attractive and practical.

We created a set of requirements for the mission. During the study we converted this from science requirements to instrument requirements within the context of an x-configuration interferometer. Through detailed analysis we then were able to create tables of tolerances for the instrument.

To reach the full potential of the mission it was necessary to incorporate baselines in excess of one kilometer between the extreme entrance apertures. At this distance we determined that there was no hope of being able to mechanically connect the mirrors and
hold them to the needed separation. Thus it was necessary to embrace the concept of placing the individual apertures that cover the UV plane on separate spacecraft. The craft would then be given the task of maintaining phase coherence across the array. Initial investigation of this concept shows it to be possible, albeit difficult. For example the mission must go to an interplanetary orbit where external torques are minimal. Similarly, we envision the craft holding relative position to 5cm while the mirrors held within are stabilized to the 1nm needed for beam coherence.

On the other hand, there is great versatility in the approach, once the problem of formation flying has been solved. The configuration can sample the UV plane in different ways for different targets. It can fly farther apart and increase resolution. Mirrors can be added or subtracted during the course of the mission.

We investigated the technical limits of the mission architecture and report the results. Surprisingly, we found that the mission was functional down to resolutions of $10^{-16}$ radians (30 pico-arcseconds). However, a very difficult problem sets in at about 10 nano-arcseconds. The visible light from the stars we usually use to establish an inertial coordinate system become over-resolved, dilute, and hence faint. There are some solutions that may allow us to penetrate into the pico-arcsecond range, but they will have to be more carefully examined in Phase II.

During Phase I we identified the key technologies will enable the mission. These are areas where we are “pushing the envelope” technically. They include:

- Mirrors polished and maintained to $\lambda/200$ after launch
- Aspect interferometers that function across multiple spacecraft and generate ultra-high resolution pointing information.
- The problem of forming a constellation of spacecraft, maintaining it and slewing it.

In summary:

In Phase I we identified a practical approach to x-ray interferometry, identified its key technologies and eventual limitations.

III. CONCEPT DEVELOPMENT PLAN

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. THE PATHWAY

The next step is 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.
Figure 15

Figure 15 is an attempt to show the pathway from the original conception of x-ray interferometry as an exciting scientific possibility through to an accurate conception of how to build such a device and where technology could be improved to make the system a reality. For each step, we show the box as green (shaded) if we now have a good understanding of the technical requirements, and a design that meets the needs with
technology that is available now (or will be within five years). The pink (stippled) boxes show the parts of process that we have addressed at some level, but are not yet fully resolved. The white boxes have not yet been addressed in any serious way.

At the start of Phase I, only the first box was filled. During Phase I we fully defined an effective mission architecture, optical design and fully tabulated the critical requirements. We were able to outline what this meant in terms of full engineering and establish that the requirements were reasonable achievable. However, we have not reached the standard by which NASA would be accepting of a mission. In Phase II we need to carry the exercise all the way to the last block.

By so doing, we will have a fully defined mission. Then, we will have established fully the reality of the concept. We will identify technical areas where infusion of technical development funds would leverage large improvements in the cost or performance of the mission. We will identify areas where technology overlaps other fields of endeavor and fully integrate the concept into NASA’s future planning.

B. DEVELOPMENT OF KEY TECHNOLOGIES

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

a) Fabricating, mounting, and thermal control of large, high quality mirrors.
   This can be approached through computer modeling. Finite element analysis of the mirror blanks and their holders. Looking at innovative techniques for reduction in mirror mount stress such as final ion polishing of the mirror after its mounted in its holder.

b) Formation flying of multiple spacecraft, including creation and slewing of the array.
   Investigate micro-thrusters and the size of spacecraft torques in interplanetary space. Look for optimal strategies to maneuver the constellation of spacecraft with minimum consumption of propellant. Seek devices and algorithms that will bring the monitor relative position and allow craft to find their places.

c) Bringing multiple mirrors into phase coherence and them holding them during the observation.
   Seek new mirror stability maintenance schemes. Allow spacecraft large deviations, but float the mirrors inside. Obtain phase coherence at long wavelengths then observe target at shorter wavelengths.

d) Monitoring of celestial sources to provide ultra-high precision aspect information.
   Develop interferometer designs that will function across huge gaps between spacecraft. Model these systems. Include size effects of the stars being tracked for stability. Watch the effects of proper motion, general relativity.

We propose to further investigate these key technologies and decrease the technical risk associated with each of these during Phase II.

This can be accomplished in two ways. First, we will identify relevant, related technologies and utilize them (steal good ideas from other projects). Second, we will be as inventive as possible in optimizing the designs trying to find better ways to solve problems as the sub-system level without impacting the overall system negatively.

C. COMMUNITY ACCEPTANCE

The science community, like most human communities, is often reluctant to embrace a new ideas and replace 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, and all we can do is keep on pointing out the realities in public at any chance we get. The second problem is the perception that x-ray optics are crude and impossibly difficult to build, thereby implying that x-ray interferometry is truly beyond any practical horizon. In truth, if one simply extrapolates the way x-ray optics have been done in the past, one would have to agree. We feel however, that we have, over the last year, shown that revolutionary approaches to the optics, such as the flat mirror interferometers fully refute that viewpoint. Again, education in the community, plus laboratory development of the x-ray interferometers will eventually change the perception at large. Unfortunately, lab development is costly and beyond the scope of this proposal. We must satisfy ourselves with developing a full technical understanding of a mission and communicating that to the public. With luck, other funding sources will support lab development.

IV. MANAGEMENT

Facilities The work will take place at the University of Colorado, Columbia University, the Massachusetts Institute of Technology, and Ball Aerospace of Boulder, CO. All four institutions have world class laboratory and computing facilities that will be available for the project. Each of these labs has supported projects of both greater and lesser complexity. Detailed description is beyond the scope of the proposal.

Grant Administration All of the institutions involved have a long successful track record of tracking expenditures and personnel. We plan to run our grants through the standard systems in the standard fashion. Columbia, MIT and Ball will perform their work through subcontract to the University of Colorado.

Budget The detailed budgets are presented in the cost section. This is primarily a conceptual development effort so needs no hardware except for some PC computing power. The money will be used for salaries, travel, and computing, and publishing expenses.

Personnel: The members of the proposing team are all highly skilled and experienced in the techniques of x-ray astronomy, short wavelength optics, and precision metrology. The team has been assembled with the goal of bringing together the diverse talents needed to solve the challenges of the program.

Webster Cash is a Professor of Astrophysics at the University of Colorado, Boulder. He holds a Bachelor of Science (Physics, 1973, Phi Beta Kappa) from MIT, and a Ph.D. in Physics from the University of California, Berkeley (1978). He has been a member of the faculty in Colorado since 1979. He specializes in the development of astrophysical instrumentation for ultraviolet and x-ray astronomy. He has been the principal investigator on numerous sounding rocket experiments and is a co-investigator on the Far Ultraviolet Spectroscopic Explorer. In addition to his astrophysical pursuits he has been inventing tech transfer applications of x-ray technology for lithography and medicine. He is a member of the American Astronomical Society, the Optical Society of America, and the International Astronomical Union. He has published over 75 papers in the professional literature and holds three patents.
Steven M. Kahn is a Professor and Chair of the Department of Physics at Columbia University. He received his A.B. (summa cum laude) from Columbia in 1975 and his Ph.D. in Physics from the University of California at Berkeley in 1980. Prior to returning to Columbia in 1995, Kahn was a member of the faculty in Physics and Astronomy at Berkeley for twelve years. He is an expert in the field of X-ray spectroscopy of cosmic sources and currently directs significant instrumentation development, laboratory astrophysics, and observational programs in that field. Kahn is the Principal Investigator for U.S. participation in the Reflection Grating Spectrometer on the European Space Agency X-Ray Multi-Mirror Mission which will fly in August 1999. He has been frequently asked to serve as an advisor to NASA and other government agencies, and is currently Co-Chair of the Structure and Evolution of the Universe Technology Working Group. Kahn is a member of the American Astronomical Society, the American Association for the Advancement of Science, and is a Fellow of the American Physical Society. He is the author or co-author of over 110 publications in the professional literature.

Mark L. Schattenburg is a Principal Research Scientist at the Center for Space Research at MIT. Dr. Schattenburg holds a B.S. degree from the University of Hawaii in 1978, and a Ph.D. from MIT in 1984. He is the Director of the Space Microstructures Laboratory and Associate Director of the NanoStructures Laboratory. His principal work has been in the area of micro/nanofabrication technology, X-ray lithography, X-ray optics/instrumentation, and high resolution X-ray spectroscopy. Early in his career, he participated in the mission planning and operations, data reduction and analysis for the MIT Focal Plane Crystal Spectrometer experiment on the HEAO-2 (Einstein) X-ray satellite, which provided high resolution X-ray spectroscopy. Most recently, he has developed techniques of nanostructure fabrication that are applicable to advanced instrumentation in X-ray astronomy. He currently leads the group responsible for the fabrication of nanometer-period X-ray transmission gratings for the Advanced X-Ray Astrophysics Facility (AXAF), scheduled for launch by NASA in 1998. He has published over 70 papers and holds three patents. He is a member of the American Vacuum Society.

David L. Windt is a Research Professor in the Department of Physics at Columbia University, having recently moved from Lucent-Bell Labs. Dr Windt holds a Bachelors of Science (1982, magna cum laude, Phi Beta Kappa) from the University of Connecticut, plus an M.S. (1985) and Ph.D. (1987) from the University of Colorado at Boulder. He pioneered the development of diffraction-limited normal incidence multilayer mirrors for soft X-ray projection lithography, developed a state-of-the-art soft X-ray reflectometer and a large-substrate multilayer deposition system, and has made contributions to our understanding of the role of substrate roughness on mirror performance, the effect of interface imperfections on multilayer performance, and stresses in multilayer films. In recent years, he has extended some of this work to solve more immediate problems in electron-beam and deep UV lithography. He is currently working to develop new types of normal incidence X-ray reflective multilayer films for solar physics and depth-graded, broad-band X-ray reflective films for use in grazing incidence telescopes for soft gamma-ray astronomy. Over the past eight years, he has co-organized a series of four meetings on the Physics of X-Ray Multilayer Structures (www.bell-labs.com/topic/conferences/pxrms). He also co-organized in 1993 a US-Japan workshop
on EUV lithography, and supervised the Bell Labs research project in this field. He has over 85 technical publications on thin films and multilayers, X-ray optics, soft X-ray projection lithography, electron-beam projection lithography, and instrumentation for X-ray astronomy. In addition, he has developed two software packages that are in wide use among the scientific community.

Dennis Gallagher is a Senior Systems Engineer at Ball Aerospace in Boulder CO. He holds a BS from California Polytechnic State University (1985) and PhD (1993) from the Department of Astrophysical and Planetary Sciences of the University of Colorado at Boulder. He has extensive experience in design, fabrication and launch of complex electro-optical systems for the space program.