

The Maxim Pathfinder Mission: X-ray Imaging at 100 Micro-Arcseconds

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ABSTRACT

Ultra-high resolution imaging in the x-ray has the potential to revolutionize the way astronomers view the heavens. Through the use of interferometry at grazing incidence we can image the x-ray sky at the milli-arcsecond (or better) level. . In this paper we describe the baseline design of the Maxim Pathfinder Mission, which will be the first interferometric x-ray observatory whose goal is to image the sky at 100 micro-arcsecond resolution in the 0.5-1.5keV band with about 100cm² of collecting area. This resolution is adequate to image the coronae of nearby stars and the accretion disks of quasars.

Keywords: X-rays, Interferometry, X-ray Astronomy, X-ray Optics, Grazing Incidence Optics

1 INTRODUCTION

X-ray interferometry is now a practical reality, and it represents an unprecedented opportunity for the astronomer. The extremely short wavelengths and the high brightness of the sources combine to allow celestial observations with thousands and even millions of times the resolution of the Hubble Space Telescope¹. The scientific return should be truly revolutionary. One can plan to take images of the coronae of the other stars, accretion disks in quasars and eventually even image the event horizon of a black hole.

In 1998 and 1999 NASA funded a study of the feasibility and importance of x-ray interferometry. Named MAXIM, for Micro Arcsecond X-ray Imaging Mission, this group (led by one of us - N. White) investigated the potential range of scientific return and the approaches to solving the technical problems. The results were compiled in a report² which should be available shortly. Other information is available at the website (<http://maxim.gsfc.nasa.gov>).

The Maxim group recommended a three phase approach to the problem.

- A technology development phase in which to learn the practicalities of x-ray interferometry as applied to astronomy.
- A Pathfinder Mission with a meter-class interferometer. With 100 μ as resolution and modest collecting area, this mission will take detailed images of the stellar coronae and probe deep into the accretion disks of quasars.
- Development toward the full Maxim, with the goal of acquiring a black hole image before the year 2020.

Maxim now appears in the advance planning for the Structure and Evolution of the Universe Space Science theme at NASA. A full capability Maxim, with resolution better than one micro-arcsecond and capability to image event horizons in AGN's is described as a "Vision Mission" for the time period beyond 2015. A more modest mission, called Maxim Pathfinder is planned for a new start in 2008.

In this paper we describe the baseline design for Maxim Pathfinder. The mission is expected to operate in the 0.5 to 1.5keV band and collect images of x-ray sources with resolution of 100 micro-arcseconds or better. With such a huge leap in capability (representing a thousand-fold improvement over HST) there exist many technical problems to be solved. In this paper we present the broad outline of the mission design and indicate how the central problems will be solved.

2 SCIENCE GOALS AND REQUIREMENTS

In order to achieve resolution of 100 micro-arcseconds at 1keV, we need an interferometer with a baseline of about 1.4 meters, achievable in a single spacecraft. For comparison, to achieve the same resolution in the radio at 6cm wavelength would require 120,000 kilometers.

The science requires that we be able to observe at 1keV, since many of the most interesting targets are obscured below 0.5keV by absorption in the interstellar medium. Adding some capability at 6keV through the use of multilayers would be very exciting, giving the mission access to the astrophysically-important Fe K line. The collecting area should be in the vicinity of 100cm². We know from previous missions like Einstein that 100cm² supports excellent work on a large variety of objects. However, missions with just 10cm² of collecting area have studied a limited range of bright targets.

We do not expect or need to move to new targets hourly. A new target every few days would allow the mission to return a spectacular set of about one hundred unique images per year. Thus modest collecting area and leisurely target acquisition are acceptable.

Table 1: Performance Requirements

Angular Resolution	100 μ as
Baseline	1.4 meters
Collecting Area	100cm ²
Field of View	10 mas
Bandpass	0.5-2keV + 6keV
Pointing	30 μ as
Spectral Resolution (E/ δ E)	20
Size	Single Launch
Orbit	High Earth or Drift Away

The stability requirements on the spacecraft are quite challenging. There is little hope of suppressing all the extraneous mechanical influences of low Earth orbit, so it appears that either a high orbit or a drift-away orbit will be required. These high orbits naturally allow lengthy observations of targets, which is valuable for high quality image reconstruction.

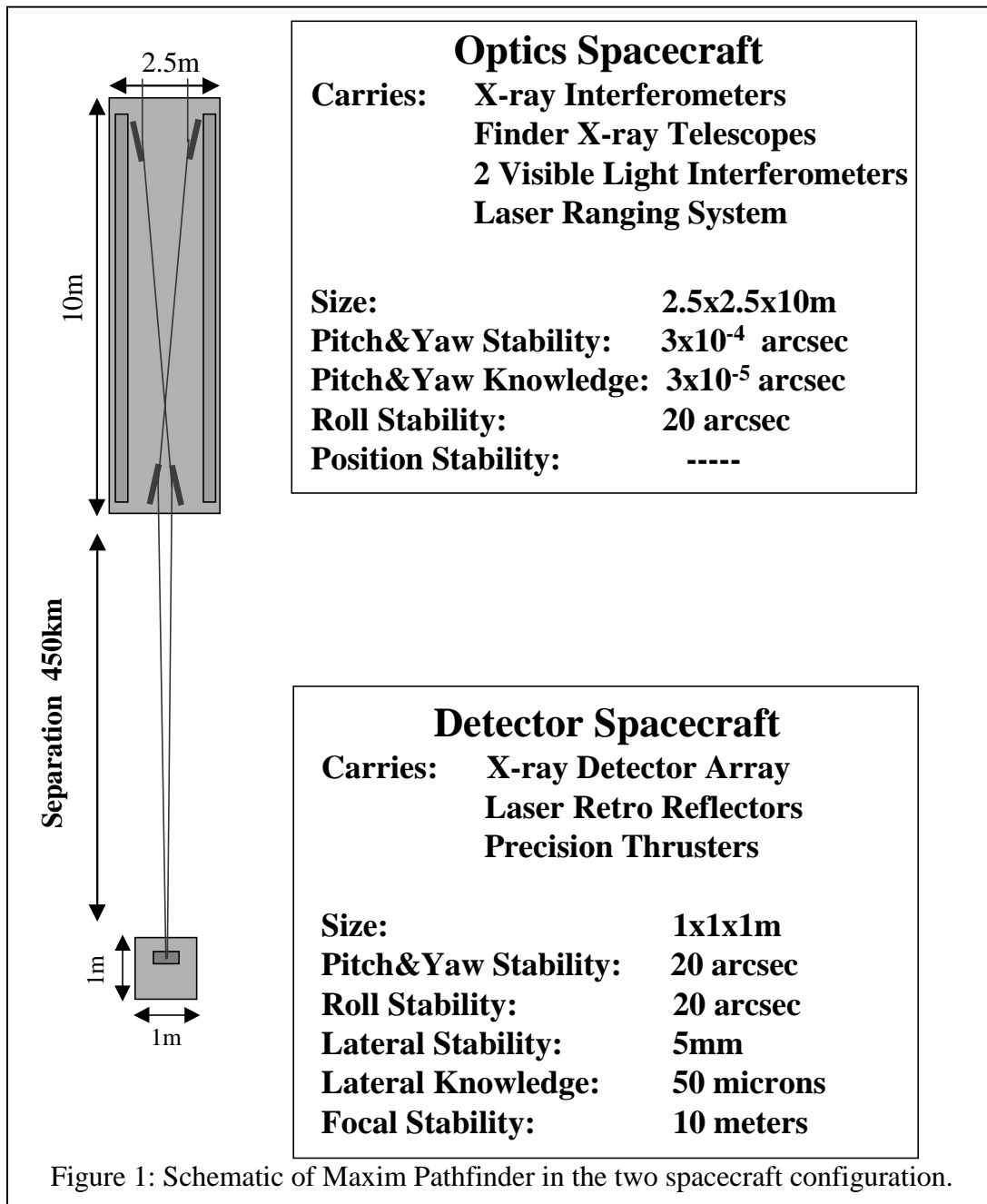
3 MISSION CONCEPT

Pathfinder consists of an array of grazing incidence mirrors on a stabilized spacecraft, creating x-ray interference fringes on the detector, which is located on a second spacecraft 450km away.

The Optics: Mirrors that preserve the x-ray wavefront are very difficult to polish and figure, even at grazing incidence. While it is *possible* to build Wolter-type x-ray telescopes that are diffraction limited, these greatly complicate the fabrication of the observatory and depress the collecting area. For this reason we have chosen to use the flat mirror concept. The interferometer will consist of two rings of flat mirrors. Each ring will contain 32 flat mirrors, each fine adjustable to achieve zero null on axis. The interferometer will have about 100cm² of effective collecting area, similar to that of Einstein and ROSAT.

Target Acquisition: Most of the science targets will boast celestial coordinates accurate to only slightly better than one arcsecond, but Pathfinder must have a way to allow the observer to center on the target of interest. As such, Pathfinder will have two x-ray optical systems, a Wolter telescope and an interferometer. The Wolter telescope will have approximately five arcseconds resolution while the interferometer will have a 1.4 meter baseline and produce the full 100 micro-arcsecond resolution. The detector spacecraft will have a 30x30cm array of CCDs. The size of the 3cm beam cast by the mirrors at a distance of 450km is only about 15 milli-arcseconds. The array of detectors increases this coverage to about 150 milli-arcseconds. If the Wolter telescope has resolution of about five arcseconds, then it should be possible to centroid the target to about 0.15 arcseconds. The first image with the interferometer can then be used to center exactly on the target.

Optics Spacecraft: The spacecraft that carries the interferometers should be about 2.5 meters in diameter and ten meters long. In most respects, such as power and mass, it will be conventional. In the area of pointing stability it must be exceptional. We need to hold the pointing stable to about 300 micro-arcseconds and provide pointing information down to about 30 micro-arcseconds. Drifts greater than 30 micro-arcseconds must not occur during the readout time of the CCD. The pointing information will be generated by two visible light interferometers that will view stars that lie in the heavens approximately perpendicular to the target line of sight and to each other.



Detector: We have chosen to use an imaging quantum calorimeter for the detector. It needs to be about 30mm square with 200 micron or smaller pixels. Energy resolution of 10eV at 1keV would nicely support the science. The optics have a very wide field of view, so an array of these 3cm CCD's will be used to increase the field for centroiding on poorly known target positions.

Formation Flying: The detector spacecraft needs to hold its position in space relative to the main spacecraft, to about a tenth of a fringe spacing. This can be accomplished using a laser ranging system between spacecraft and microthrusters to offset drifts. This capability is comparable to that needed in the LISA mission, but is in some ways easier as they need to measure acceleration while we care only about position.

Orbit: Because the two spacecraft need to be stable relative to each other and to the celestial sphere, we must move the mission away from the turbulence of low Earth orbit. We expect that either a flyaway orbit or a Lunar Lagrangian point would be appropriate.

4 OPTICAL DESIGN

4.1 Layout

To avoid the potential difficulties of building diffraction limited Wolter x-ray optics, we have baselined the flat mirror interferometer in the “x” configuration as demonstrated in the laboratory^{3,4,5,6}. Table 2 summarizes the characteristics of the interferometer design, while Figure 3 shows the layout of such a system schematically in two dimensions.

This reduces the optics problem to its absolute minimum. Flats are the easiest mirrors to fabricate and to align. The problem is that to achieve adequate fringe magnification the beams must cross at a very low angle. To magnify 1nm waves to 100 micron fringes requires a cross angle of about 2 arcseconds, which implies that L will be large.

The size of L is in turn driven by the size of d, the spacing between the flats in the beam converger. Our design requirement of 100cm² enters here. We will need 32 flat mirrors in a ring to achieve a nice field of view, so each mirror channel should have about 3cm² of effective area.

Allowing for losses due to the two reflections and the detector, we find the aperture should be 3cm square. Fitting 32 such mirrors in a ring requires a 30cm diameter, which we use as the baseline separation in the beam converger.

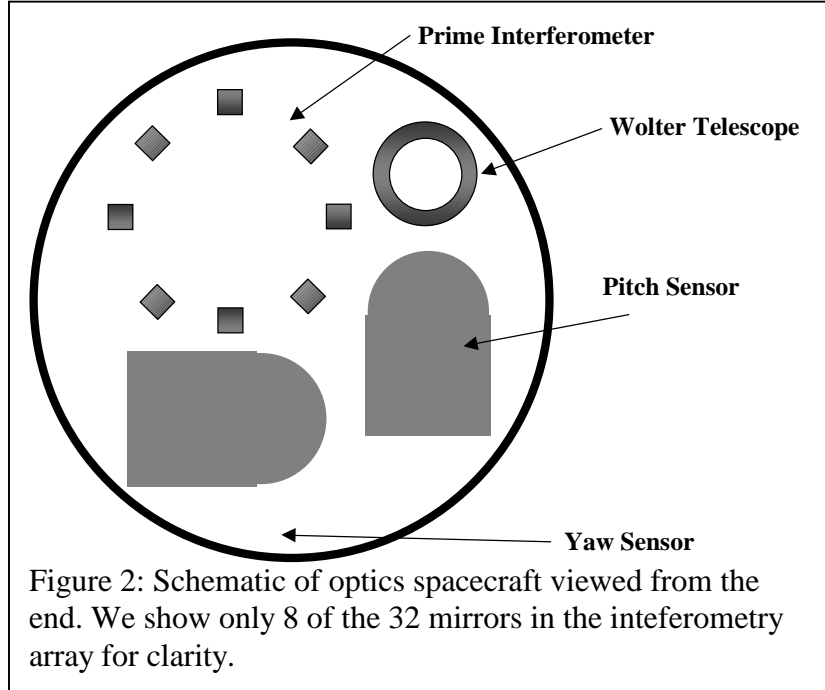


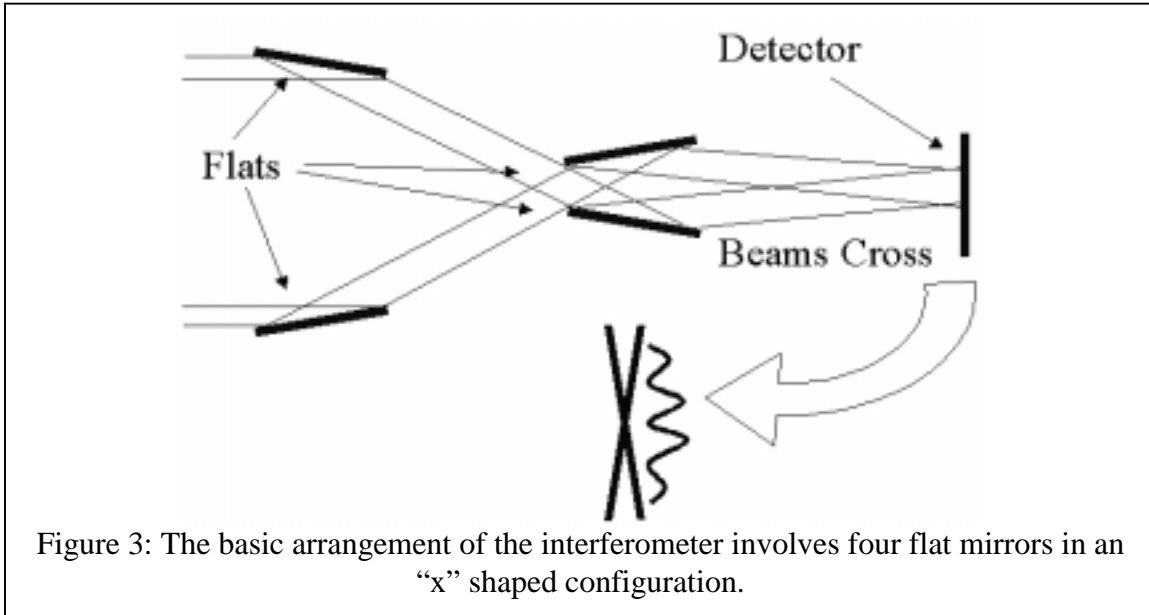
Figure 2: Schematic of optics spacecraft viewed from the end. We show only 8 of the 32 mirrors in the inteferometry array for clarity.

Table 2: Interferometer Characteristics

Primary Ring Diameter	140cm
Secondary Ring Diameter	30cm
Distance: Primary to Secondary	1000cm
Distance: Secondary to Detector	450km
Mirror Size	3x90cm
Graze Angle	2 degrees
Number of Primary Mirrors	32
Number of Secondary Mirrors	32
Mirror Quality @ 6328Å	$\lambda/400$
Mirror Coating	Ir + Multilayer
Resolution @ 0.25keV	360 μ as
Resolution @ 1keV	90 μ as
Resolution @ 6keV	15 μ as
Fringe Width @ 1keV	2mm
Fringe Width @ 6keV	0.3mm
Field of View	10 mas
Bandpass	0.1-2keV+6keV

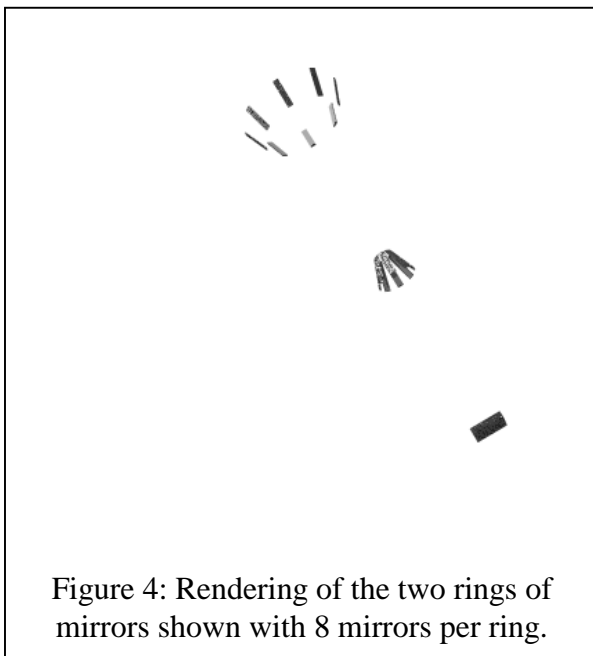
beam converger.

The effect of bringing 32 flats in a ring into phase coherence is dramatic as shown in Figure 4. The figure is a simulation of the pattern resulting from a monochromatic point source. With two mirrors the detector records the expected sine wave. With four mirrors we find a checkerboard. As the number of mirrors rises, the pattern first becomes complex, and then starts to clear out the region around the central point of constructive interference. We are, effectively, building a diffraction limited telescope out of flat subapertures. As the pointing changes, the bright spot moves around the field of view just as in a telescope. For the 32 mirror case, an excellent image 64x64 pixels in extent is achieved without inversion of



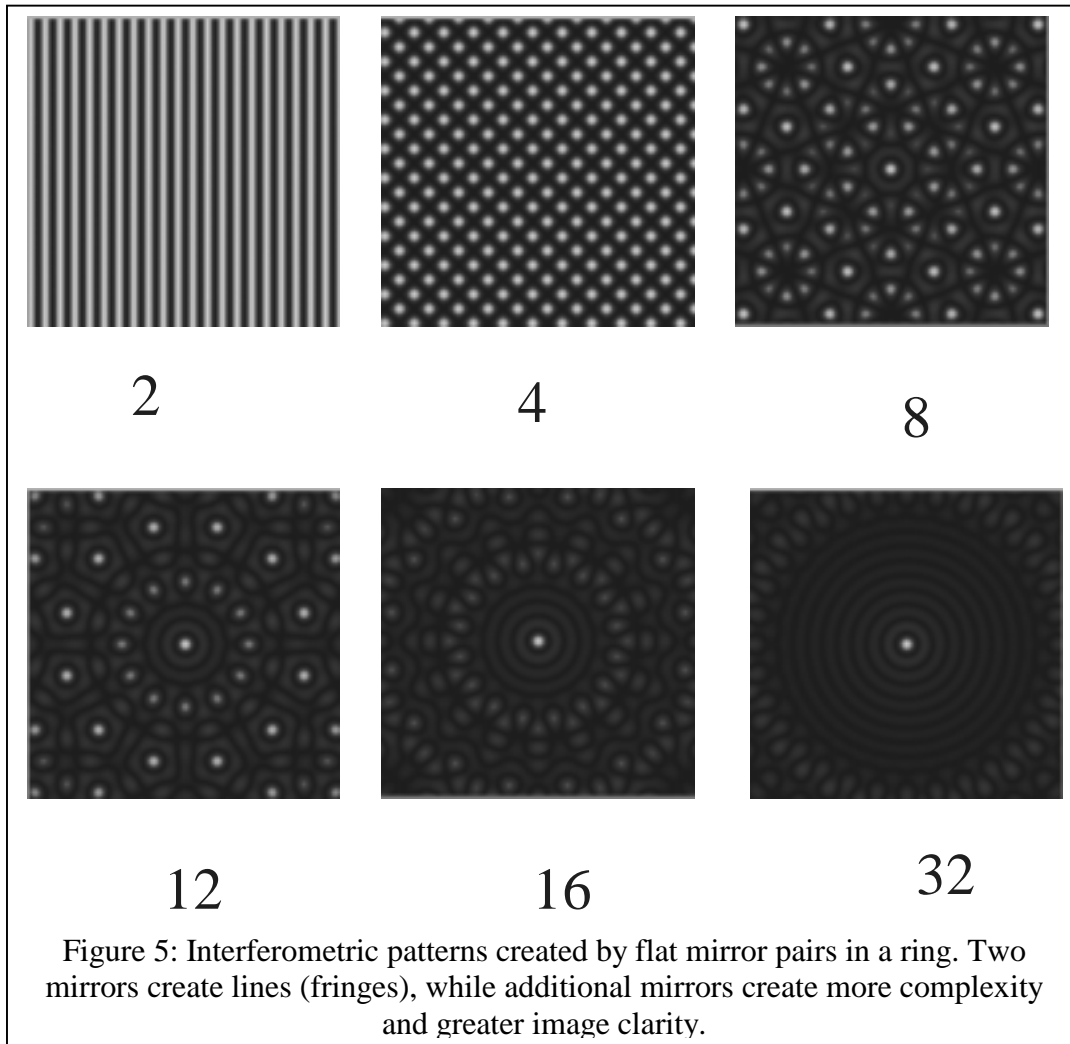
fringes. For wider fields of view, there is a substantial power to be found in the surrounding rings, that must be removed through image processing.

Thus, an interferometer consists of two rings of flat mirrors. In Figure 4 we show a 3-D rendering of the arrays. We show only 8 mirrors per ring for clarity, when the interferometer will have 32 per ring. Each mirror will be mounted on precision actuators that will allow in-flight alignment. The mirrors themselves will be 3cm wide and 90cm long. They can be as thick as desired because there is no nesting envisioned. The total amount of glass in each interferometer is about the equivalent of a 1m square mirror.



The primary ring of the interferometer will consist of 32 mirrors with actuators in a ring 1.4 meters in diameter. The resolution of such a ring is given by $\lambda/2D$, where D is the diameter of the ring. This supports resolution of $70\mu\text{as}$ at 1nm, and $100\mu\text{as}$ at 0.9keV. At 6keV, using the multilayer reflection, the resolution reaches $14\mu\text{as}$.

Note that the resolution is given as $\lambda/2D$, not the usual λ/D . The usual formula is appropriate for a filled aperture telescope, where, when the outer edges of the mirror are 180 degrees out of phase, most of the center is still in phase. Also, consider that in an interferometer, an angle change of λ/D will cause a the a full fringe shift, but we can resolve two stars when they are half a fringe out of phase, indicating the resolution is $\lambda/2D$. Our use of a single ring creates large diffraction rings, but it also doubles the resolution.



4.2 Mirror Requirements

An x-ray interferometer is a sensitive device. The lengths of the paths that the x-rays travel are sensitive to errors in position and angle in the mirrors. They have to be held to a fraction of an x-ray wavelength, which means 100 picometers. This would be extremely challenging except that we are once again rescued by the geometry of grazing incidence.

Figure 6 shows an analysis of the position tolerance for a flat mirror reflecting a plane wave at grazing incidence. In the direction of the mirror normal we find that the position tolerance is relaxed by a factor of $1/\sin\theta$ relative to a normal incidence reflection. For 1nm radiation, we typically use a 2 degree graze angle, which, when inserted into the formula implies that the mirror must be held to about 1.5nm relative to the mirror on the other side of the interferometer if the fringe is to be held to one tenth of a wavelength. This is the tightest metrological tolerance.

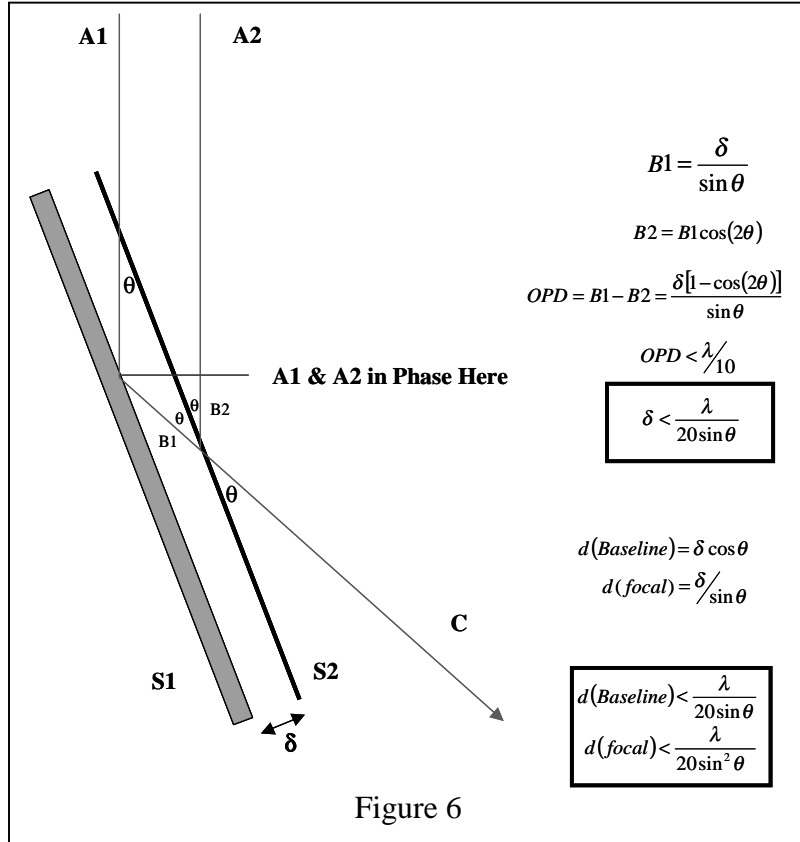
Figure 6 shows an analysis of the angular tolerance for each mirror in the interferometer. Its tightest tolerance is for an angular deviation in the in-plane direction. The figure proves that each mirror should be held to one tenth of its own diffraction limit. This makes sense, as there is no optical information below the diffraction limit except at the fraction of a fringe level. For Pathfinder we find that each mirror must be aligned and held to about one milli-arcsecond if it is to hold the tenth fringe requirement.

This is an area that needs substantial development before flight. The tolerances are stringent and at the state of the art. We need to develop both the mirrors and their holders for flight⁷.

5 DETECTORS

5.1 Prime Science

The interferometer creates fringes across the field of view. In the case of the ring of 32 flats, the field of view resembles a point source with a strong diffraction ring around it. The radius of the central point and of



the rings around it is a linear function of the wavelength of the radiation. Since we will be observing sources with a broad continuum of emission, the rings will blur out and potentially degrade the image.

To be able to process the image and achieve the best possible images from the system, we need to be able to record the energy of each photon as it strikes. The first, strong ring is at about ten fringe amplitudes from the center. If we are to be able to position the position of the ring to 10% of its width, then we need to know the energy to one part in a 100. Thus, a detector that can resolve photon energy to better than 10eV at 1keV is desirable.

For this reason we use an imaging quantum calorimeter as the baseline detector for the system. Such systems are not available today, but will

be within a few years⁸. Since the fringe spacing is 2mm, the 200μ spatial resolution available is highly appropriate.

It should be noted that the mission is not totally dependent on the imaging calorimeter. Without a CCD the system can still function, just with a somewhat degraded image quality and more expensive optical system.

Table 3: Mirror Alignment Tolerances

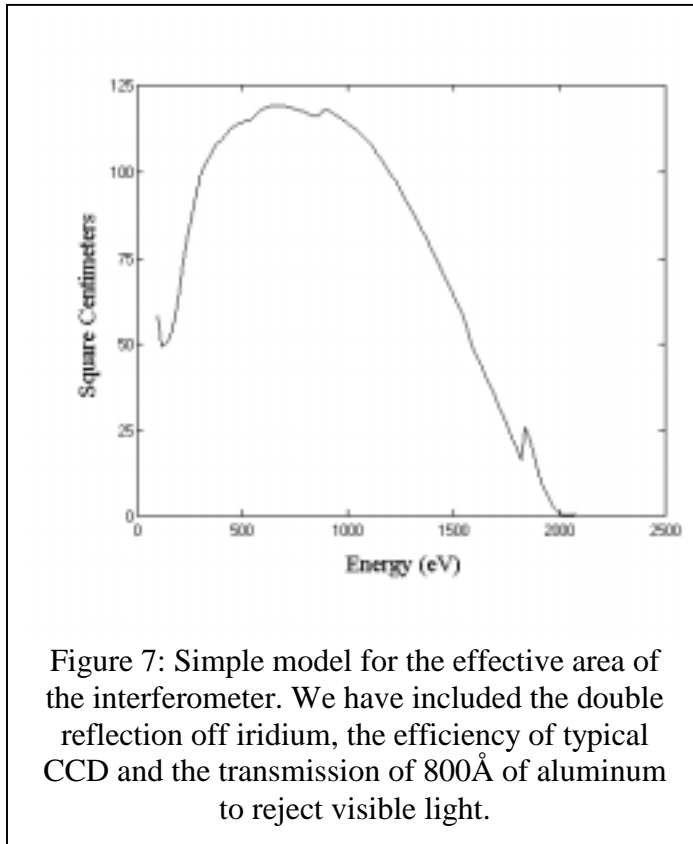
X Position	δx	$\lambda_x / 20\theta$	1.5nm
Y Position	δy	$\lambda_x / 20\theta^2$	45nm
Z Position	δz	---	1mm
θ_x Angle	$\delta\theta_x$	$\lambda_x / 10d$	1mas
θ_y Angle	$\delta\theta_y$	$\lambda_x / 10d\theta$	30mas
θ_z Angle	$\delta\theta_z$	---	1 degree

30cm square. The purpose of this detector array is target acquisition. As discussed in section 7, a large field of CCD's coupled should allow us to find our target and bring it into the sweet spot at the center of the field of view. Conventional CCD's filtered for x-ray performance should suffice. They will not have to run after the target is acquired.

5.2 Target Acquisition

Around the core area where the interferometer functions and the signal falls upon a quantum calorimeter, we expect to place an array of CCD's

6 INSTRUMENT PERFORMANCE



6.1 Collecting Area

The effective area is shown in Figure 7. It reaches 100cm² around 0.5keV and holds a high level to near 1.5keV. It falls severely near 2keV. Figure 7 does not show the narrow throughput spike at 6keV that can be added by the use of multilayers.

6.2 Resolution

The resolution of the interferometer is given by $R = \lambda/2D$, where R is the resolution in radians, λ is the wavelength and D is the separation of the primary mirrors. For the Maximum Pathfinder this becomes $R = 3.6 \times 10^{-10} \lambda$ where λ is the wavelength in nanometers and R is the resolution in radians. Converting to resolution in micro-arcseconds, $R = 74\lambda$. Converting the equation to energy units, $R = 92/E$ micro-arcseconds, where E is in keV.

The Maxim Pathfinder will have resolution of about 200μas at the low energy end of its bandpass (0.5keV) improving to about 60μas at the upper end (1.5keV). If we are able to make the interferometer work at 6keV using

multilayers, the resolution will be 15μas.

6.3 Data Analysis

Data analysis should be straightforward. The photons will be corrected for any detected drift and binned to form an image. The image, if it is taken in the wide field configuration will contain the strong diffraction rings. These can be greatly reduced by computer enhancement of the image, using the known point response function. These algorithms usually need a good signal to perform well, so the faintest of the targets will be hard to clean up.

7 TARGET ACQUISITION

Some of our targets will have celestial coordinates accurate to milli-arcsecond level, having been observed by SIM, but many will not. Some targets cannot be observed in the visible, others are too faint or in confused fields. Even if we tried to use this information, building an instrument to re-establish that coordinate system would be difficult. It appears we need a “finder scope”.

Our approach is build a modest size Wolter telescope. This will only 10 or 20cm² to function well, as its purpose is to locate the target, given coordinated good only to a few arcseconds. This Wolter can have resolution as large as 5 arcseconds and use the 10meters of the optics spacecraft as its focal length. Better resolution would be helpful in target acquisition, and it is likely that a Wolter in 0.5 to 1 arcsecond quality range will be affordable in this timeframe. The target would be acquired within its field of view based on conventional startracker pointing. Pathfinder would center the target to within one resolution element of the center. Centroiding should then provide pointing to about 0.15 arcseconds.

Because of the relatively large error we have created a large detector array at the focal plane. At 450km, a 30cm detector subtends 0.15 arcseconds, enough to find the source. Pathfinder can then complete the pointing. Thus, the detector array is designed for the crucial business of finding our target. However, the interferometer will generate an image, unblurred by aberration across the whole field, so there is a bonus scientific return for a target that has angular extent of a hundred milli-arcseconds instead of just ten.

During the early phases of the mission, the relative alignment of the instruments will need to be calibrated and adjusted so that the acquisition of targets can proceed smoothly. There is no chance that the relative alignment of the instruments will survive launch, so in-flight co-alignment will be needed.

8 POINTING

Target acquisition can take place in the x-ray, but maintaining the pointing of the main spacecraft cannot be done in the x-ray with our existing instrumentation. We suggest instead to fly two visible light interferometers – one for pitch and one for yaw. We need both as the interferometer is two-dimensional in performance.

The interferometers will resemble those on Space Interferometry Mission⁹ in that they will feature two apertures about 10 meters apart, feeding telescopes that create a white light null fringe. SIM will be able to achieve 4 micro-arcsecond information, so our requirements are directly achievable using their approach.

Because our targets are scattered around the sky, we need to be able to find nice, bright reference stars at any arbitrary pointing position. SIM, through the use of an optical delay line, is able to work with stars in a fifteen degree square of sky. This ability solves our needs nicely. Unlike SIM, however, we do not need astrometry. We only need the drift information relative to the null, greatly simplifying our operation.

One might question that a visible light interferometer, with its big, floppy photons, would be able to steer an x-ray interferometer. There are two reasons why this works. First, the baseline of the visible interferometer is longer by a factor of seven. Visible light across 10meters gives fringes that are separated by 10 milli-arcseconds. Second, and more importantly, the aspect stars are bright. The null fringe can be centroided to one part in 300, to achieve the sensitivity needed at the 30micro-arcsecond level. SIM expects to centroid another factor of 8, all the way to 4 micro-arcseconds.

9 FORMATION FLYING

The detector is located on a separate spacecraft that can be as far as 450km from the mirrors, and yet it must be held properly in place. This will be accomplished with the use of precision thrusters on the detector craft reacting to position signals from the optics craft.

We take the philosophy that the detector craft will be slaved to the position and orientation of the optics craft. This has the advantage of keeping the detector on the optic axis, not the physical axis. Within this philosophy, the position of the optics craft does not matter, but it is very sensitive to angle relative to the celestial sphere. The angle of the detector craft is very forgiving – it need only be pointed in the approximate direction of the optics craft, but its position relative to the optics craft is quite sensitive.

	Optics Craft		Detector Craft	
	Stability	Knowledge	Stability	Knowledge
Pitch	300μas	30μas	1degree	10arcmin
Yaw	300μas	30μas	1degree	10arcmin
Roll	10arcmin	1arcmin	10arcmin	1arcmin
X Position	---	---	3mm	150μ
Y Position	---	---	3mm	150μ
Z Position	---	---	100m	100m

The beam exiting the converger mirrors at the back of the optics spacecraft is extremely slow, meaning that the depth of field is very large, many meters or more. Thus we do not need to control the detector spacecraft position particularly well in the focal direction or in orientation. Arcminute class stability is fine for the image on the detector.

The difficult direction is lateral drift. Here we must hold the spacecraft in alignment to a small fraction of a fringe. The fringe spacing at 1nm is 1.5mm, and we wish one tenth fringe information, so 150μ information

is adequate. (For full capability at 6keV the number would have to be tightened to 30 μ .) The field of view is large enough that knowledge at the 3mm level (20 pixels) will be acceptable.

When a positional drift is detected, micro-thrusters must be used to correct the error. Such a system is under development for the ST-3 mission. Similarly, LISA will need formation flying and large spacecraft separations monitored by lasers, so Pathfinder should have an excellent technical base to draw upon.

For Pathfinder we need to design a system that will allow positional information of 150 μ at a distance of 450km. We have two possible approaches under consideration: laser ranging and interferometric patterning. Both use laser systems mounted on the optics craft.

9.1 Coarse Positioning

At the start of any observation, after maneuvering, the detector spacecraft must be flown to approximately the correct position along the optic axis of the optics craft. To do this, the detector craft must know the position in the sky at which the optics craft is pointing. Then it must move to the position along the line

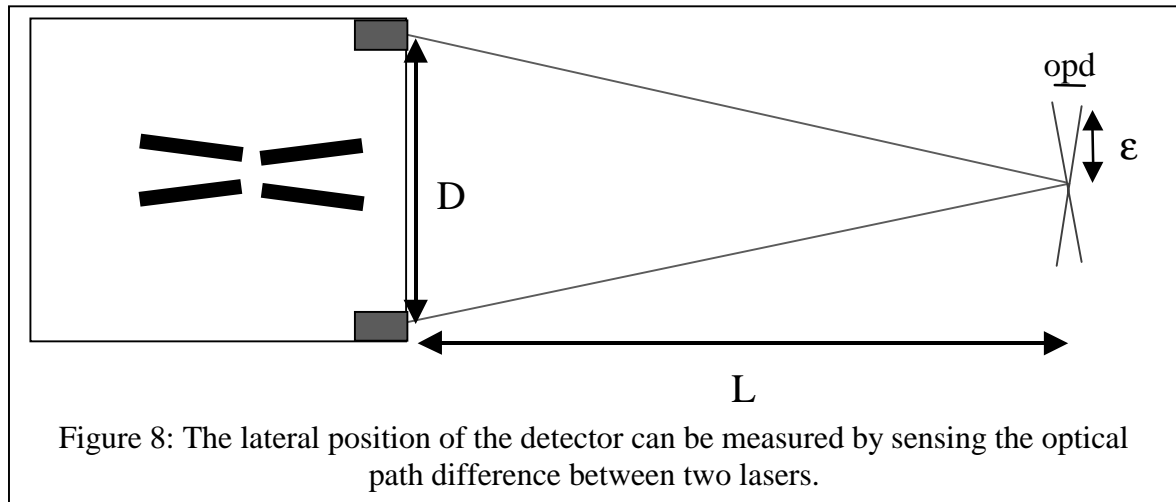


Figure 8: The lateral position of the detector can be measured by sensing the optical path difference between two lasers.

extending from the target, through the optics craft and 450km beyond. This can be accomplished to the needed accuracy of a few meters using conventional radar.

9.2 Laser Ranging

We looked at using laser ranging to provide the needed stability. We found that this approach is marginal, and maybe not be practical at all across the large (450km) gap between the craft.

Consider Figure 8. We place two lasers two meters apart at the back end of the optics spacecraft, shining at the detector craft. As the detector drifts to the side, the pathlengths from the two lasers will start to diverge by an amount:

$$opd = \frac{D}{L} \epsilon$$

where ϵ is the size of the lateral drift. Noting that ϵ/L must be held to about 30 micro-arcseconds, and D is about 2 meters, then we find that the opd must be detectable at the 0.3nm level, or $\lambda/2000$.

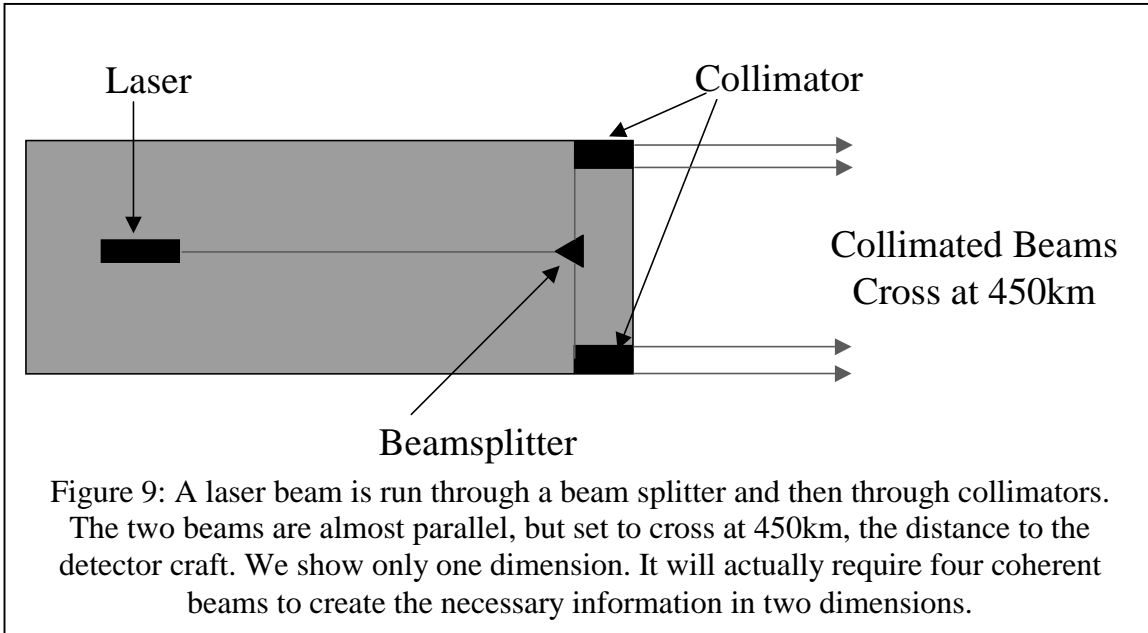
The biggest single problem with this approach is in the wavelength stability of the laser. The ranging operates by counting fringes between the two endpoints. We need $\lambda/2000$ of a wavelength information across 450km, which implies one part in 2×10^{15} . This is just beyond the limit of laboratory lasers and well beyond flight lasers. In short, we would need serious development to make this work.

An alternative is to split the laser beam and do ranging with the two parts. Since we do not need absolute distance, only path difference, it might be possible to compensate for wavelength drift by interfering the two beams against each other. This might bring the ranging into spec, but it needs further, careful study.

9.3 Position Patterning

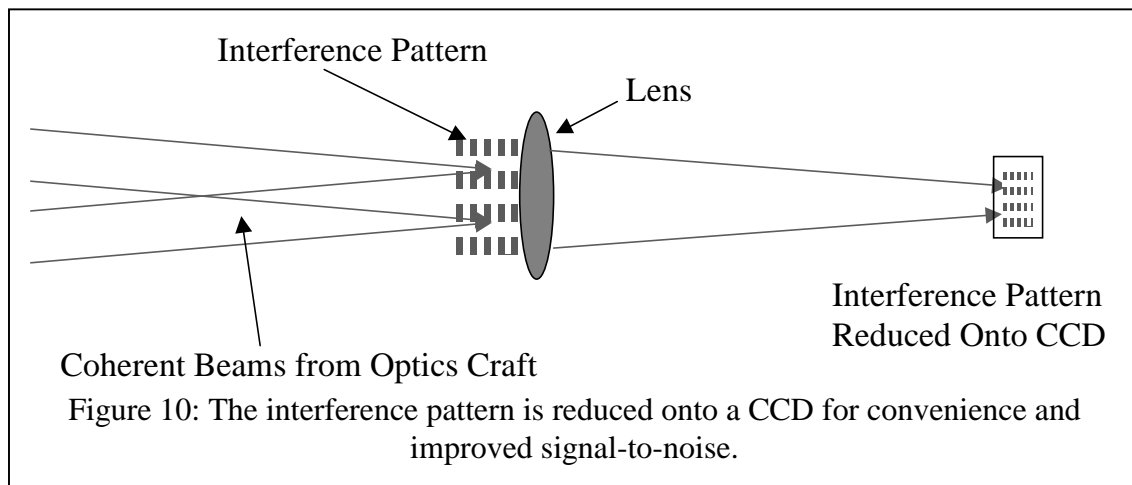
In response to the problem of laser ranging we proposed an alternative approach to positional knowledge. It also uses lasers and should solve the problem.

Consider Figure 9. On the optics spacecraft we mount a single laser. The beam is run through two beam



splitters in sequence, creating four beams of equal intensity that emerge parallel to each other and to the optic axis of the interferometer. A typical laser will have .001 radians of beam divergence so that, when the beams reach the detector craft they will be 450m across.

Because the beams are coherent, they will create a two-dimensional square fringe pattern at the detector

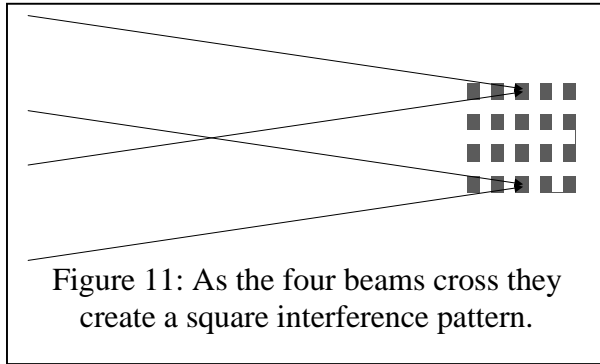


craft. If the exit apertures of the beams on the optics craft are D meters apart, and the detector craft a distance L from the optics craft, then the fringes at the detector will be a distance s apart, where:

$$s = \frac{\lambda L}{D}$$

and λ is the laser wavelength. For $L=450\text{km}$, $D=4.5\text{m}$, and $\lambda=6328\text{\AA}$, we find that the fringe spacing s is 63mm. To achieve 150μ knowledge, we will need to centroid the wave to one part in 400, which is directly achievable if there is adequate signal-to-noise.

To achieve good signal to noise we suggest the arrangement shown in Figure 11. The interference pattern is an array of squares at the detector craft, but they are large. If they are gathered by a lens (or mirror) of



roughly 50cm diameter, then roughly 8x8 array of fringes will enter the lens. These fringes should not be focussed, but rather concentrated. For example, a 50cm f/4 lens will have a 2 meter focal length. If a CCD is placed 1.9m behind the lens (95% of the way to the focus) the pattern will be reduced from 50cm to 2.5cm in diameter. The fringes will drop from 63mm to 3mm across. The output of the CCD can then be analyzed to detect shifts in phase, and hence in lateral position.

The 50cm lens will collect approximately of 10^6 of the flux from the lasers. A 50mW laser

emits 5×10^3 ergs/sec, so the system will collect and detect 5×10^9 ergs/s in the CCD. This is about 1500 photons/s. To achieve centroiding of 600:1 we need 600^2 photons, or 3.6×10^5 photons. This requires 200 seconds which is probably a bit too long.

To improve the sample cycle time down to a few seconds we could increase the power of the laser. A 5W laser would reduce the cycle time to a few seconds. However, the use of collimators on the output of the lasers is more practical. For example, if each of the four beams exiting the optics craft is run through a 10cm diameter collimator lens, then the diffraction pattern is reduced in angle from 10^{-3} radians to about 5×10^{-6} radians, thereby reducing the extent of the diffraction pattern from 450m to about 2m. The spacing of the fringes is unchanged, but the alignment of the collimators becomes much tighter. The brightness of each fringe is improved by 4×10^4 , which then allows excellent signal to noise in the CCD in well under one second. The optimal trade between signal spread and signal sensitivity will require more careful study.

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