# Development of optics for sub-micro-arcsecond angular resolution in the X-ray and gamma-ray domains

**Abstract**

We argue that several related technologies hold the promise of achieving X-ray or gamma-ray imaging down to the sub-micro-arc-second level – the resolution that is necessary to image space-time in the immediate environment of super-massive black holes. Over the next decade these should be studied and further developed in order to select an optimum strategy and be ready for flight in a subsequent decade.

Submitted by
G. K. Skinner
NASA-GSFC & CRESST & Univ. Md.
301-286-1350
gerald.skinner@nasa.gov

On behalf of
Z. Arzoumanian, NASA-GSFC & CRESST
W. Cash, Univ. Colorado
K. Gendreau, NASA- GSFC
P. Gorenstein, Harvard - SAO
J. Krizmanic NASA-GSFC &CRESST & USRA
H. Marshall, MIT
R. Reasenberg, Harvard - SAO
D. Windt, Reflective X-ray Optics, LLC

# 1 The challenge of sub-micro-arcsecond imaging

We have shown in a Science White Paper [1] that major advances could be made in our understanding of black holes, active galaxies, and other astrophysical objects by instrumentation capable of imaging at the sub-micro-arc-second level. It would become possible to image the space-time surrounding the supermassive black holes at the centers of galaxies, providing crucial tests of general relativity as well as elucidating how these objects interact with their environment, often accelerating jets that can extend to scales up to $10^7$ or more times larger. At the same time attaining this angular resolution would make feasible many other entirely new observations, including imaging the surfaces of nearby stars, as well as opening up a massive new discovery space by improving angular resolution by up to 6 orders of magnitude over that possible with current optical and X-ray instrumentation.

Other science white papers that have been submitted to the Decadal review have discussed both the need to test general relativity where it is strong and highly non-linear [2, 3, 4, 5] and the importance of very high angular resolution [6, 7, 8, 9], and/or ultra-precise astrometry [10, 11, 12, 13, 14]. Others (*e.g.* eg [15, 16]) stress the importance of Black Hole physics. Thus the developments discussed here push in directions that are clearly widely regarded as important even though the techniques advocated are not always the same and the ambitious limits emphasized here are not always targeted.

# 2 How could such an advance be possible?

The scale of the problems facing attempts to improve angular resolution to the extent proposed here can be seen in Fig. 1. Simple consideration of diffraction means that instrumentation must have at least the characteristic size (baseline for an interferometer, or aperture diameter of an imaging optical system) shown. Considering one micro-arc-second as the watershed at which the radical new science sought here starts becoming possible, it can be seen that one is driven to the X-ray and $\gamma$-ray bands. Fortunately, the sources of most interest are intrinsically very bright in these bands (to

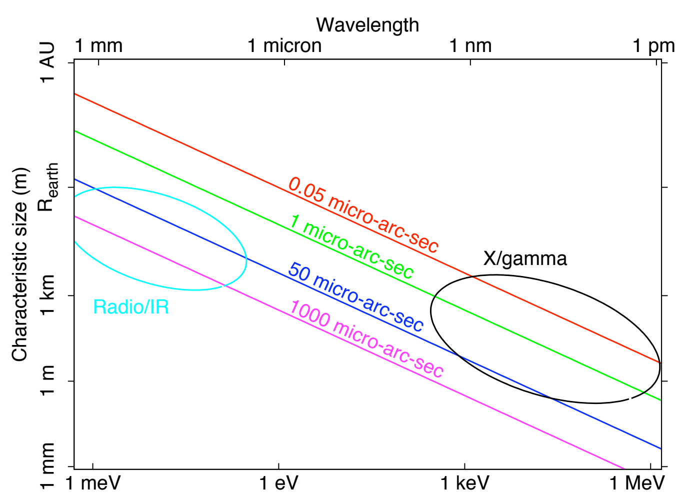


Figure 1: The characteristic size (aperture diameter or maximum baseline) needed to achieve different angular resolutions as a function of energy or wavelength. The two ellipses indicate the general region of parameter space targeted here and that accessible to VLBI and IR interferometry.

the extent that the emission may be considered to be thermal, the compactness of the regions makes this inevitable; even non-thermal sources contain densities of high energy particles and photons that lead to the same conclusion).

Except at the highest energies, or for angular resolutions that are closer to milli-arc-second than micro-arc-second, the instrument size is considerably greater than that of an aperture needed to collect an adequate signal. Thus it is natural to consider sparse aperture instruments. In the limit of very sparsely filled apertures such instruments are usually referred to as interferometers but as the number of baselines increases, the point source response function becomes closer and closer to that of a true imaging system. In the gamma-ray band sub-micro-arc-second **filled** aperture instruments in the form of lenses of a few meters or tens of meters in diameter become feasible. Even in the this case, for reasons discussed below, interference effects must still be considered and there is in practice a continuum of possibilities between the two extremes of interferometry and imaging.

Whether it is to a single image point of an imaging system or to form fringes in an interferometer, incoming X/$\gamma$ radiation spread over the input aperture has to be concentrated upon a common detector. A number of possibilities exist:

1. Grazing incidence reflection
2. Normal incidence reflection from multilayer mirrors
3. Diffraction, perhaps combined with refraction

Each of these has been proposed as the basis of instrumentation capable of reaching the goals under discussion here. Surprisingly in each case it turns out that, although further development is needed, **a large part of the technology necessary is already in place**. We will consider the implications of each approach in turn and review the current status.

# 3 The range of possibilities

## 3.1 Grazing incidence interferometers (GII)

### 3.1.1 GII : The concept

The use of grazing incidence reflection as the basis of an astronomical X-ray interferometer has been extensively discussed as the basis of the MAXIM mission concept. Using a single grazing incidence mirror to redirect each beam towards a common fringe detector would be problematic in several respects. As the effective area is the area of the polished area multiplied by $Sin\theta$, where $\theta$ is the grazing angle, $\theta$ cannot be too small. Typical values are of the order of 1°. If two beams are made to intercept in this way after a single reflection then the angle between the wavefronts is $4\theta$, and the fringe spacing $4\theta/\lambda$, leading

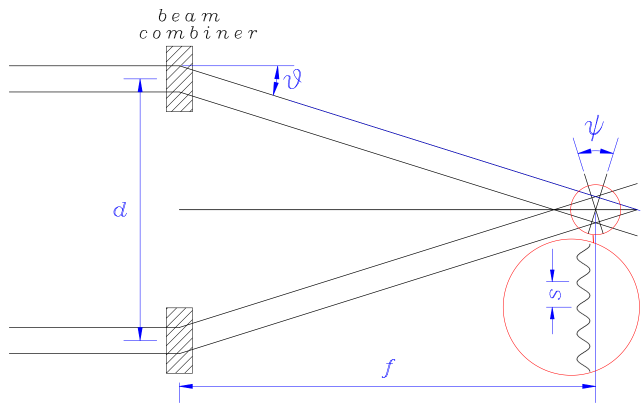


Figure 2: A simple generic interferometer. The fringe spacing is $s = \lambda/\psi = \lambda/2\theta = \lambda d/f$

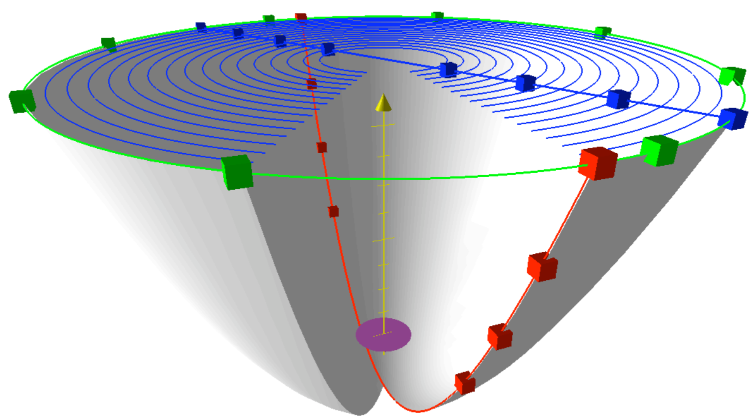

Figure 3: Optics options for interferometers and imagers. If radiation from a distant source is diverted from any point on the parabolic surface (eg the red symbols or the green) towards the focal point indicated by a disk, the path length will be the same and the radiation will arrive in phase. A lens covering the plane indicated in blue operates by changing the phase of radiation to compensate for the path length difference. If interferometric beam diverters are distributed in this plane, the path length is the same for a circular configuration (green). However other arrangements (such as the along the blue line) require delay lines to compensate for different paths or only work for one carefully chosen wavelength, of which the path differences are chosen to be exact multiples. 'Normal' incidence reflectors would populate a part of the bottom of the paraboloid.

to impracticably fine fringes. This problem can be avoided by using two mirrors. Use of two mirrors per unit also allows the different path-lengths when the beam combiners are not all the same distance from the axis to be compensated by changing the mirror spacing. Multiple periscopes of this form can then direct radiation towards a single detector plane as shown in Fig. 4.

Even a two mirror unit is extremely sensitive to changes in the orientation of the diverter units. This sensitivity can largely avoided by a further doubling of the number of mirrors, leading to the 4-mirror periscope configuration shown in Fig. 5 that would in practice replace the two-mirror units in Fig. 4. To a large extent it is then only the internal alignment within a periscope unit and the distance between units that is critical.

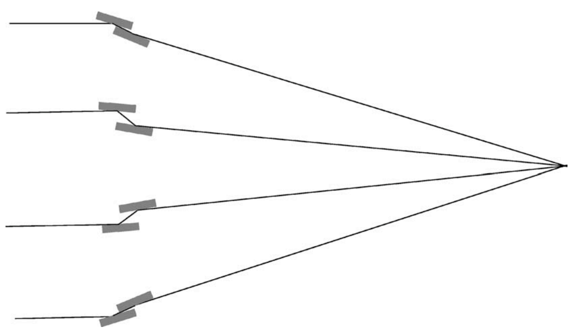

Figure 4: An interferometer using pairs of grazing incidence mirrors to combine the beams.

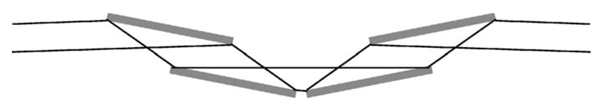

Figure 5: A four mirror periscope that can replace the beam diverters in the interferometer in Fig. 4.

#### 3.1.2 GII : The current situation

Grazing incidence mirrors are of course the work-horse of X-ray astronomy and the technology is well developed. Reflection at grazing incidence, as well as being extremely efficient has the advantage that the effect of mirror figure errors is much reduced (by a factor $\sim Sin^{-1}\theta$) compared with normal incidence and the required polishing precision is already readily achievable. The formation of fringes by combinations of grazing incidence mirrors has been demonstrated in the laboratory [17, 18]. The tolerances and system design for 4 mirror periscopes have been well studied [19]. Grazing incidence periscopes are the basis of the MAXIM mission concept [20]. MAXIM pathfinder mission concept was the subject of a GSFC Integrated Mission Design Center (IMDC) run in 2002 (Fig. 6). The periscope optics were studied by the GSFC Instrument Synthesis and Analysis Lab (ISAL) in 2003. No 'show-stoppers' were identified in either case.

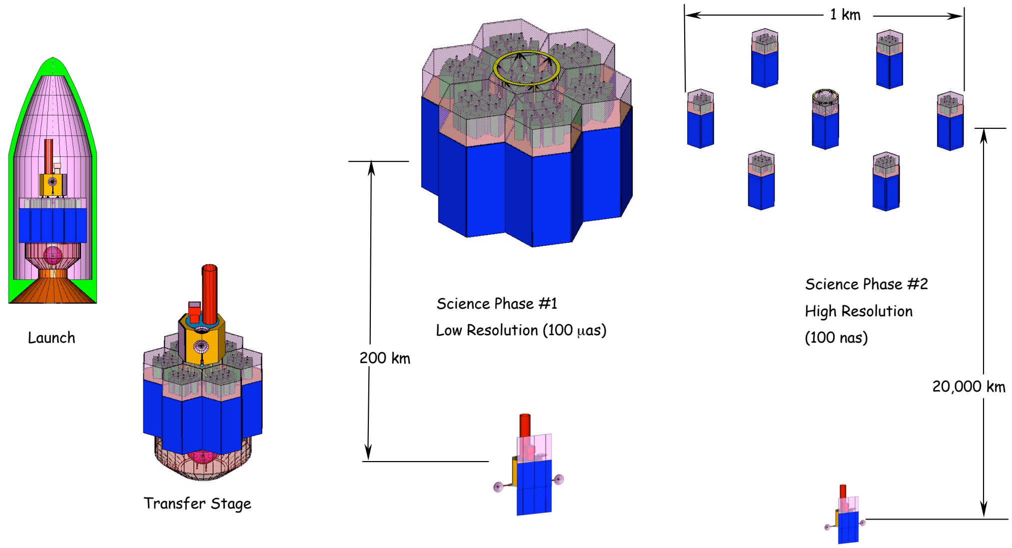


Figure 6: The pathfinder and final MAXIM configurations studied at the IMDC in 2002.

## 3.2 Diffractive/refractive optics (DRO)

### 3.2.1 DRO: The concept

It has been pointed out [21] that Phase Fresnel lenses (PFLs) a few meters in diameter working in the gamma-ray band can achieve the target angular resolution. In the X-ray band lenses must be larger for the same resolution, but the same technique can be used. Such lenses rely on the phase shifts that occur when X/$\gamma$- radiation passes through a thin sheet of material. They can have a very high efficiency and because they work in transmission they are unaffected by even quite large offset errors (tilts) of the lens axis with respect to the line of sight. Furthermore they are lightweight compared with mirror optics. However they are chromatic, with a focal length proportional to photon energy. Achromatic combinations can be formed by combining the diffractive Fresnel lens with a refractive lens, but in practice the refractive component has to be stepped in thickness to avoid excessive absorption (and mass) [22, 23, 24] . This leads to a lens in which the best performance occurs at a comb of energies within a bandpass corresponding to $\Delta E/E \sim$10–20% [25]. The energy range can be further increased by devoting different parts of the lens surface to different energy bands. An other disadvantage of PFLs is that the focal lengths tend to be long, particularly for high energies – values of $10^5$ km or more have been discussed. Diffractive optics is most efficient at energies where the thickness of material necessary to produce the required phase-shift is relatively transparent. For a simple PFL this is above a few keV up to $\sim$MeV; refractive correctors to make achromats tend to require higher energies, from a few tens of keV upwards.

If used at X-ray energies, the very large aperture that would be needed to achieve sub-micro-arc-second angular resolution suggests that in this case a partially filled aperture would be used. Small sections of lens could be carried on different spacecraft flying in formation. Within a single section the curvature of the grooves and variation in their pitch would be small and they can be regarded as a series of variable pitch, blazed, diffraction gratings directing the radiation towards the common detector.

A variation of this arrangement in which the diffraction gratings have constant pitch has the interesting property that the fringes formed are achromatic (though for finite sized gratings the band over which the beams cross and the fringes **are** formed is limited). This effect is related to Talbot effect that has been harnessed for phase contrast microscopy and the configuration has been suggested for astronomical applications [26].

Thus, depending on how the design a sparsely filled array of diffractive (/refractive) optics falls a different points along the continuum between an imaging system and an interferometric one.

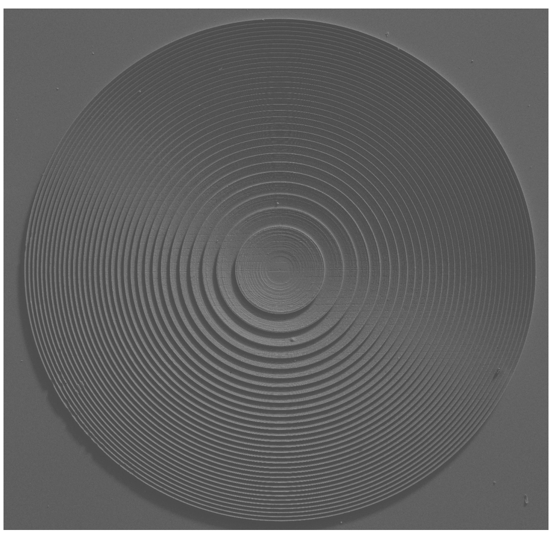

Figure 7: A small (3mm) Phase Fresnel Lens fabricated in Silicon using grey scale technology. By mosaicking subunits larger than this, but with structures no finer, Phase Fresnel Lenses many meters in diameter (and with corresponding longer focal length) may be made.

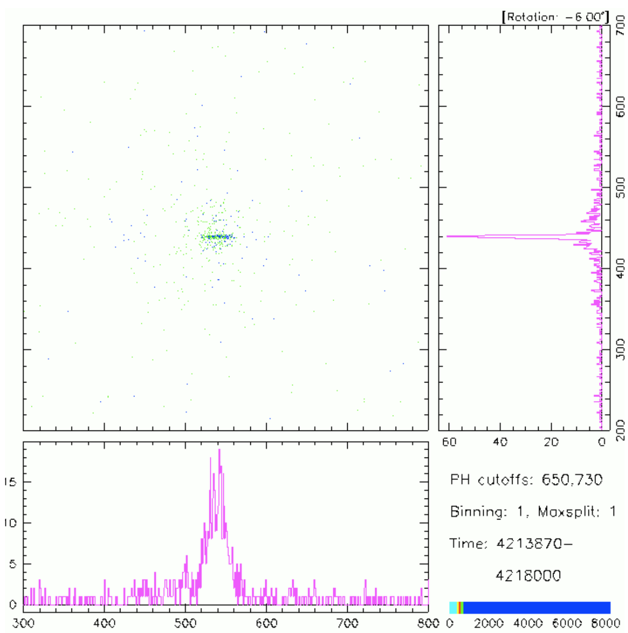


Figure 8: An image of a 10 micron by 40 micron source obtained with an achromatic refractive/diffractive lens.

#### 3.2.2 DRO: The current situation

Fresnel lenses are widely used for X-ray microscopy, particularly at synchrotron facilities. For such applications the challenge is to make the **linear** resolution as good as possible and this drives one to extremely fine groove spacing and very limited diameters (eg tens of nm and  100 microns, respectively). What is needed for astronomy is *angular* resolution and large aperture. To a very good approximation this simply means a radial scaling, without changing the thickness; one moves away from nano-engineering towards easier and more conventional machining techniques.

Although manufacture would be relatively easy, testing a lens suitable for astronomical applications is problematic because of the very long focal lengths. However lenses on a scale intermediate between those for microscopy and what is needed for astronomy have been demonstrated in the GSFC X-ray interferometry testbed (Fig. 7). So far diameters have been up to 5mm and energies up to 17 keV. Achromatic diffractive/refractive lenses have also recently been constructed and demonstrated (Fig. 8). The concept of using diffractive beam combiners for interferometry and the achromatic nature of the fringes formed has also been demonstrated at the same facility (Fig. 9) and methods are under development for interferometric testing of sections of large lenses.

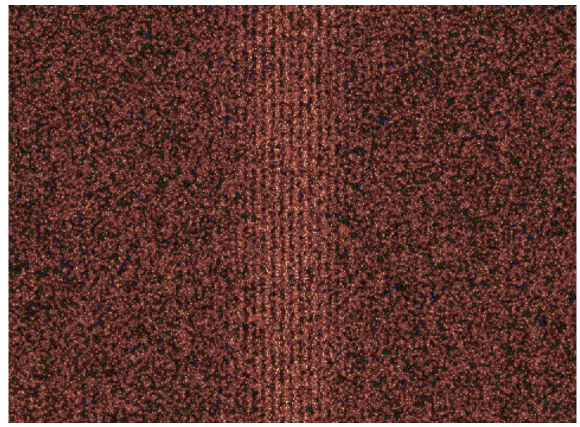

Figure 9: Achromatic fringes obtained with diffractive beam combiners. The events recorded are a mixture of Cu K$\alpha$ (8.04 keV), Cu K$\beta$ (8.90 keV) and continuum radiation. The fringe pitch is 101 microns, corresponding to an angular resolution of 46 milli-arcseconds, independent of energy.

IMDC studies of a FRESNEL mission concept using diffractive/refractive lenses for micro-arc-second imaging at gamma-ray energies and of a less ambitious FRESNEL Pathfinder mission with lower resolution in the hard X-ray band were conducted in 2002. A milli-arcsecond X-ray pathfinder (MASSIM) was proposed in response to the 2007 NASA solicitation 'Astrophysics Strategic Mission Concept Studies' [27]. A bibliography of papers on the DRO approach is available [28].

### 3.3 Normal incidence interferometers (NII)

#### 3.3.1 NII: The concept

At energies below $\sim$1 keV ($\lambda >\sim 12$Å) multilayer techniques allow normal incidence reflectors to made [29]. These are most efficient in a narrow band around the particular wavelength for which they were designed but this can be chosen to coincide with that of an astronomical line of interest, such as the $\lambda = 33.7$Å emission line of C VI $L_\alpha$ observed in many astrophysical plasmas. It then becomes possible to imagine a classical configuration as indicated in Fig. 10 with an aperture of several km, sparsely filled with normal incidence reflectors.

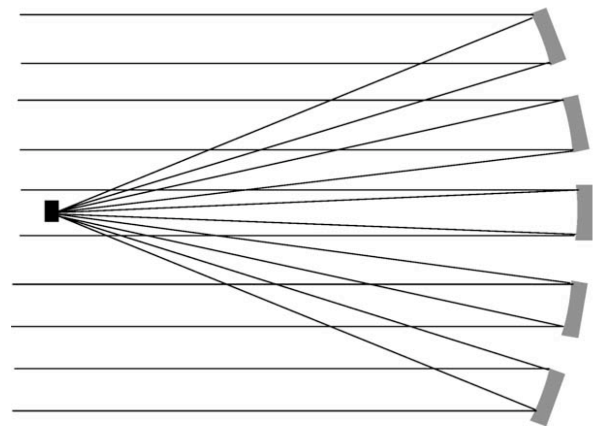

Figure 10: An interferometer / imager based on normal incidence multilayer optics.

#### 3.3.2 NII: The current situation

It is perhaps not widely recognized among the astronomical X-ray optics community that diffraction-limited X-ray mirrors have already been developed, and are, in fact, now in regular use. A concerted worldwide effort driven by the international semiconductor industry has been directed at the development of diffraction-limited EUV imaging systems for photo-lithography, an approach known as Extreme Ultraviolet Lithography (EUVL) [30]. The EUVL imaging systems utilize multilayer mirrors with coatings tuned to $\lambda \sim$134 Å, where the reflectance of normal-incidence Mo/Si multilayers has approached 70%. The multilayers are deposited onto aspherical mirror substrates as large as 20 − 25 cm in diameter. As a result of the EUVL effort, large-diameter mirror substrates having 1-2 Å figure and finish specifications are now commercially available, as are new metrology tools needed to characterize these substrates and facilitate their fabrication, such as the LLNL point-diffraction interferometer operating in the visible, as well as synchrotron-based at-wavelength interferometers, both having sub-nm precision. The EUVL substrates are diffraction-limited to $\sim \lambda_{134A}/50$, and at the shorter soft X-ray wavelengths of interest for astronomy, to $\sim \lambda_{34A}/10$, or$\sim \lambda_{17A}/5$, sufficient to construct a two-reflection diffraction-limited astronomical telescope.

New ultra-short period multilayer coatings have recently become available that are designed for normal-incidence reflection in the soft X-ray band appropriate astronomical observations. In particular, two systems, Cr/Sc and W/B4C, now can be used as normal incidence mirror coatings in the range $\lambda$ =16 − 40Å. These coatings can be deposited onto large-diameter figured mirror substrates, using multilayer deposition systems that are capable of sub-angstrom control of the coating thickness uniformity,

## 4 What is needed - ultra high resolution optics and related technologies

The three possible technologies discussed here have different advantages - among them the relative simplicity of a two spacecraft solution possible with the DRO approach at the highest energies, the access to the Fe line of GII or DRO in the X-ray band, and the benefits of existing developments in EUV technology for NII. It is not yet clear how scientific priorities may change over the next decade nor how the practicability of different technologies may evolve. In order that a valid trade-off study can be undertaken to narrow down the field of possibilities, each of the technologies requires further study and demonstration that its peculiar technical difficulties can be overcome.

Were the optics issues the only consideration, it would perhaps already be possible to be considering detailed plans for a mission. More challenging are the developments of formation flying of 2 or more spacecraft and determination of the orientation of the cluster in celestial coordinates to the precision necessary to take advantage of the capabilities of the optics. Both of these technologies are of interest to other potential missions as well (particularly to exoplanet missions) and the need for technology development in them is being presented a separate white paper [31] . We fully endorse those proposals.

If these exciting possibilities are to become reality during following decades, study and development of the optics as well as of these related support technologies must take place during the 2010-2019 timeframe.

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