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ABSTRACT

We have proposed the development of X-ray interferometry as part of ESA’s Voyage 2050 programme, to reveal the universe at high energies with ultra-high spatial resolution. With only a 1 m baseline, which could be accommodated on a single spacecraft, X-ray interferometry can reach 100 µas resolution at 10 Å (1.24 keV) and exceed that of the Event Horizon Telescope at 2 Å (6.2 keV). A multi-spacecraft ‘constellation’ interferometer would resolve well below 1 µas. Here we focus on the single-spacecraft interferometer design and discuss the process of fringe detection and image reconstruction from multiple baselines, showing simulated images of test cases from our Voyage 2050 White Paper. We also discuss the challenges and feasibility of reaching the technical requirements needed for a single-spacecraft interferometer. Most key requirements are already feasible or within easy reach. Besides a ground-based testbed, covered elsewhere in these proceedings, the most important areas for development include large format, small-pixel X-ray detectors and pointing which is stable or can be reconstructed to tens of µas precision.

Keywords: X-rays, interferometry

1. INTRODUCTION

Astronomical imaging is an extremely powerful tool to understand our universe and in recent decades observatories across much of the electromagnetic spectrum have made great strides, improving both in sensitivity and angular resolution. As shown in Figure 1, observations from radio to ultraviolet have effectively become diffraction limited with increasing angular resolutions, either through high quality optics or through connecting telescopes to form powerful interferometers. The most spectacular example of the latter is the Event Horizon Telescope (EHT) in the sub-mm band, famous for its remarkable image of the accreting supermassive black hole in M87, which reached most of the world’s population through print and online media.

Imaging performance at X-ray and shorter wavelengths is still more than 4 orders of magnitude away from becoming diffraction limited. This is due to the short sub-nm wavelengths of the light and demanding constraints for manufacturing focusing, grazing incidence X-ray optics with sufficiently accurate shapes. Currently planned and foreseen missions improve substantially in collecting area but either not at all or at best only marginally on the sub-arcsecond angular resolution attained by Chandra. Instead, X-ray astronomers have looked to significant improvements in spectral resolution, very large area detectors for fast timing, focusing hard X-ray optics or X-ray polarimetry for advances in the next decades.

This is a pity, because astronomical X-ray sources are perhaps uniquely suited to being imaged at the X-ray diffraction limits of microarcseconds (µas) and below. X-ray sources are often extremely compact, associated with some of the most energetic processes in the universe such as accretion on to compact objects and the acceleration of ultra-high energy particles in shocks or powerful jets. They produce compact and penetrating emission from a wide variety of emission processes, thermal, non-thermal, bound and free, so both their diagnostic potential and the variety of source types are significantly greater than in radio wavebands with comparable resolution from earth-sized interferometric baselines.

Therefore, in response to the European Space Agency’s 2019 call for themes for new science missions and technology development in the 2035–2050 time frame, ‘Voyage 2050’, we have proposed the development of astronomical X-ray interferometry. The work builds on existing studies carried out from 2000-2010, starting with the detection of X-ray interference fringes in the lab followed by a NASA-sponsored study into X-ray interferometry from space using a constellation of formation-flying mirrors and a separate detector spacecraft. Despite the ground-breaking nature of these studies, the extremely challenging formation-flying requirements (with tens of thousands of km spacing between mirror and detector spacecraft) seemed particularly difficult to realise without significant impetus towards formation flying spacecraft in other fields. However in 2004, Willingale proposed a compact design that could enable sub-100 µas resolution imaging from a single-spacecraft X-ray interferometer. Such a mission could potentially be realised in the Voyage 2050 timeframe and form a stepping stone to compact constellation interferometers. We describe and develop this concept further here, but also note

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Figure 1. Comparison of actual angular resolution (circles) with the theoretical diffraction limit (crosses) for existing and foreseen telescopes from radio to X-rays. Only X-ray telescopes remain far from the theoretical limit.

here for completeness that separate concepts are also being developed for ultra-high resolution using focusing X-ray optics\textsuperscript{15} or gratings which apply the Talbot interference effect.\textsuperscript{16} These efforts are described elsewhere in these proceedings.

In Section 2 we introduce the basic principles and design of Willingale’s interferometer. We describe the principles of fringe formation, field of view and image reconstruction in Section 3 and also show some example simulated images, based on the science discussed in our original White Paper.\textsuperscript{8} In Section 4 we consider the technical constraints and how to achieve them in order to realise a single-spacecraft X-ray interferometer. We make brief concluding remarks about future development of X-ray interferometry in Section 5. A separate paper in these proceedings, by R. den Hartog et al., describes the path-length tolerances in more detail along with a design for an interferometric testbed on the ground.

2. A COMPACT INTERFEROMETER DESIGN

The core operating principle is that of the Michelson interferometer and is shown in Figure 2. Two beams of X-ray photons from the distant target are collected (in this case by grazing-incidence mirrors, with grazing angle $\theta_g$), separated by a baseline $D$ and with central wavelength $\lambda$ and bandwidth $\Delta \lambda$. The beams are brought together at a point on the detector. Provided that the optical pathlength difference $\Delta P$ of coincident rays from each beam is less than the longitudinal coherence length $l_{\text{coh}} = \lambda^2 / \Delta \lambda$, interference fringes will form on the detector. The fringes are produced by the changing pathlength difference of the rays from each beam, which increases along the baseline direction as the distance from the $\Delta P = 0$ coincidence point increases, so that the fringe spacing is given by $\Delta y = \lambda / \theta_b$, where $\theta_b$ is the angle between the coincident beams. For $\lambda = 10$ Å, $\theta_b = 6$ arcsec yields small fringe spacings $\Delta y = 34 \mu m$, which are detectable with current CCD-type detectors (assuming $\sim 10 \mu m$ pixels).

The very narrow offset angle ($\theta_b$) between the beams implies an extremely large effective focal length $F = D / \theta_b$, if a single pair of collector mirrors is used to both collect the X-rays and combine them at the detector (Figure 2, panel a). For example, the original NASA studies of the Micro-Arcsecond X-ray Imaging Mission\textsuperscript{10} (MAXIM) and Black Hole Imager\textsuperscript{13} (BHI) constellation concepts envisaged baselines made up of collector spacecraft, each consisting of a set of four mirrors in a periscope arrangement to achieve stability of the outgoing beams, which were combined at a single detector spacecraft. The requirement of a narrow angle between
The interferometer’s combination of collector mirrors with axial combiner mirrors affords a long effective focal length \( F \) (see panel a) with compact interferometer dimensions (see panel b and note that vertical and horizontal dimensions are on different scales throughout). Collector mirrors \( M_1 \) and \( M_3 \) form the baseline \( D \), directing parallel X-ray beams (of width \( W_b \)) through twice the grazing angle \( \theta_g \), to combiner mirrors \( M_2 \) and \( M_4 \). Mirror \( M_2 \) is slatted (panel d) to admit the beam from \( M_4 \), with slats/gaps of width \( w \) so that the offset angle \( \theta_b \) causes a position-dependent optical path difference on the detector, enabling fringes to form (panel c). By alternating the slat pattern on the vertical halves of the mirror (right of panel d), fringes in the shadow of slats in one half of the mirror can be recovered in the gaps of the other half.

The combined beams for baselines up to 1 km (for sub-\( \mu \)as resolution) led to an extremely large collector-detector separation of \( \sim 30,000 \) km.

Willingale’s design\(^{14}\) (Figure 2, panel b) greatly reduced the collector-detector separation by a factor \( \sim 4\theta_g/\theta_b \), by adding a second pair of mirrors very close to the optical axis, which form the narrow offset angle between the beams. The second mirror of this axial pair is slatted to enable X-rays from the first mirror to pass through the gaps and form the combined beams with the X-rays reflected from the slats (Figure 2, panel d). For completely overlapping beams, the beam offset angle is then given by \( \theta_b = w/L \), the ratio of the projected slat width \( w \) to the distance \( L \) of the slat from the detector (Figure 2, panel c). This latter distance is set by \( N_f \), the required number of fringes that can fit within a combined slat/gap sub-beam at the detector, so that \( L = N_f (\Delta y)^2/\lambda \). With this set-up, an X-ray interferometer with up to \( \sim 1 \) m baselines could plausibly be accommodated on a single spacecraft with maximum dimension < 20 m.
3. INTERFEROMETRIC IMAGE RECONSTRUCTION

3.1 Fringe pattern on the detector

As shown by Willingale, the optical path difference $\Delta P$ between ray paths along each arm of the interferometer from a distant point source, which combine at position $y$ along the baseline direction is given by

$$\Delta P = -\Delta L \left( \frac{1}{\cos(\theta_b/2)} - 1 \right) + 2y \sin(\theta_b/2) + D \sin \theta,$$

where $\theta$ is the off-axis angle of the point source and $\Delta L$ is the offset distance between the two combining mirrors along the optical axis. The small extra path difference caused by this offset can be corrected by a small change in one of the collector mirror positions, so we ignore it here.

For monochromatic photons, single-photon interference results in cosine fringes with normalised intensity $I = 1 + \cos(2\pi \Delta P/\lambda)$, so that, following Equation (1), the fringes are equispaced with spacing $\Delta y = \lambda/\theta_b$. However, astronomical source X-ray spectra are generally broadband, so that the ability to distinguish different wavelengths depends on the energy resolution of the detector. Photons of different wavelengths which cannot be resolved will produce overlapping fringes with different spacings, so that the fringes are spatially limited to a coherent ‘envelope’.

The fringe relative amplitude, or visibility, $V$, which is related to the coherence of the coincident X-rays is defined as:

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}},$$

where $I_{\text{min}}$ and $I_{\text{max}}$ are the minimum and maximum intensities of the fringes. Assuming that photons resolved by the detector are drawn from a Gaussian distribution of photon wavelengths centred on $\lambda$ with Full Width at Half Maximum (FWHM) $\Delta \lambda$, the fringe envelope contains $N_E \approx \ell_{\text{coh}}/\lambda = \lambda/\Delta \lambda$ fringes with $V > 0.5$. Thus for X-ray detectors with $\Delta E$ FWHM energy resolution, $N_E = E/\Delta E$ strong fringes can be detected from the X-ray continuum, in the pair of completely overlapping beams produced by a single baseline set of mirrors.
For an off-axis point source the coincidence point ($\Delta P = 0$) of the interferometer is offset to a position $y = -D\theta/\theta_b$. Note that due to the compactness of the Willingale design (with focal length $F >> L$), this offset is much larger than the actual ($-\theta L$) shift of the rays on the detector compared to those from an on-axis source. The offset in terms of the number of fringe spacings is $N_{\text{off}} = y/\Delta y = -D\theta/\lambda$. This means that a pair of point sources equal in brightness will produce cancelling fringes when their separation is $\theta_r = \lambda/2D$, giving the effective interferometric resolution (see Figure 3, left panel).

### 3.2 Field of view and fringe sampling considerations

The relation between offset angle and $y$ position of the coincidence point sets the Field of View (FoV) of a baseline to be $FoV = \theta_b W_b/D$, where $W_b$ is the width of a beam. This follows because the fringe spacing $\Delta y$ on the detector corresponds to angle $2\theta_r = \lambda/D$ and the $FoV$ is equal to the number of fringes that could fit in the beam multiplied by $2\theta_r$. Increasing the beam width increases the number of fringe spacings that fit in the overlapping beams on the detector, while increasing the beam offset angle shrinks the fringe spacing and hence also allows more fringe spacings to fit within the beam width. However, since the number of strong fringes from a point source is restricted to the number in the fringe envelope $N_E$, only part of the overlapping beams may produce detectable fringes. We can define a fringe sampling efficiency

$$f_{\text{samp}} = N_E \frac{2\theta_r}{FoV}$$

which corresponds to the fraction of the overlapping beam width which samples fringes. For $f_{\text{samp}} < 1$ there is a reduction in signal-to-noise of fringe detection compared to the situation where fringes are detected across the entire beam.

There is, therefore, a trade-off between the efficient sampling of fringes using the full beam and the size of the Field of View. Unless $N_E$ is very large, a large field of view will lead to fringes with lower total signal-to-noise, $S/N \propto \sqrt{f_{\text{samp}}}$. Conversely, the efficiency of fringe sampling (and associated $S/N$) can be maximised at the expense of $FoV$ by reducing the mirror projected widths to $W_b \simeq N_E \Delta y$. Such a configuration could be achieved without changing the dimensions of the collecting mirrors and outer combining mirror ($M_4$), by modifying the construction of the slatted mirror so that the optical path difference is zero at the centre of each slat/gap sub-beam pair on the detector, i.e. the slat/gap pairs effectively act as separate interferometer arms.

$N_E$ can generally be increased by increasing the detector energy resolution. However, it is important to note that the shape of the fringe envelope depends on the intrinsic resolution of any emission picked up by the selected detector channels. Therefore, emission lines which are intrinsically narrow will contribute to larger $N_E$ than the underlying continuum, where $N_E$ will be limited to the detector resolution. This means that more efficient fringe sampling can be achieved for sources with narrow emission features, provided only few of these features contribute in a selected detector channel range. Furthermore, the interferometric signal of narrow band emission features can be cleanly separated from that of the underlying continuum, which enables some powerful tests of the structure of spectrally complex emission regions, even for relatively limited spatial resolution $\theta_r$.

Even for $W_b \gg N_E \Delta y$, the beams are broken up by the slatted combining mirror ($M_2$) into smaller slat/gap sub-beam pairs, which are required to enable small beam offset angles. The slats will impose an alternating pattern of shadow and illuminated bands on the detector with slat/gap sub-beam widths $w$. If the number of fringes in an illuminated band $N_f < N_E$, the missing fringes can be recovered by modifying the slatted mirror to alternate the positions of the bands on the upper and lower halves of the detector.\(^{14}\) Reducing the slat/gap widths allows for larger fringe spacings on the detector, but with a corresponding reduction in FoV for fixed baseline beam size $W_b$. Furthermore, the slats impose a diffraction pattern on the detector which distorts the fringe envelope, but can in principle be calculated and corrected for.

### 3.3 Image sampling and baseline configuration

The offset of fringes produced by off-axis sources is also responsible for the interferometer’s capability to resolve extended sources and produce X-ray images. Sources which are extended over a range of angular offsets along the baseline direction, $\Delta \theta \gg \theta_r$, produce fringes with a wide range of phases which combine incoherently to reduce the visibility of the fringes to zero. So both the phase and amplitude of fringes contain information about

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1. Modified from the original text for improved readability.
the source structure. Equivalently, the interferometer is sampling the Fourier transform of the sky X-ray image, on angular scales $\sim \lambda/D$, projected on to the baseline direction.

As with any interferometric imaging, in order to reconstruct the image within the Field of View, it is necessary to sample a wide range of baselines to cover a range of angular scales and projections on the sky. In Fourier terms, we must sample the $uv$-plane, where $u$ and $v$ denote spatial frequencies in each ($y$ and $z$) dimension of the image, such that the spatial frequency probed is given by the projected baseline dimension normalised by wavelength, i.e. it is $D_{\text{proj}}/\lambda$. Sampling in angular scale is achieved primarily (for fixed wavelength) by changing the baseline length $D$, i.e. by placing the collecting mirrors closer together or further apart. This can be achieved by successively nesting pairs of smaller baselines inside larger baselines, or more efficiently, by running multiple interferometer arms corresponding to the same baseline in parallel, with the vertical dimension used to stack baselines of different lengths on top of one another (see Figure 4).

A range of spatial scales can also be sampled by obtaining fringes over a range of different X-ray wavelengths with the same baseline, provided that the fringes at the different wavelengths can be resolved. This approach requires that the image does not strongly depend on wavelength, which will likely not be the case for many resolved sources. On the other hand, energy-resolved X-ray imaging (or astrometry) will be a scientifically important task for any X-ray interferometer.

Different projections on the sky can be sampled by orienting baselines in different directions, but we can also take our lead from ground-based interferometers where a larger range of projections are sampled via the Earth’s rotation of the otherwise fixed baselines between telescopes. Rotation of the spacecraft about the optical axis can efficiently and uniformly sample all angular projections provided that the motion of the spacecraft does not perturb optical path differences significantly. In principle then, one only needs to construct baselines along a single direction which is rotated. However, it will be useful to consider at least perpendicular sets of baselines, to deal with any systematic errors in pointing direction along a given axis. Such a configuration could also halve the required detector area, since the perpendicular sets of fringes could easily be recovered from the detector plane, if the detector spatial resolution is the same in both its dimensions. However, the cost of measuring fringes in both dimensions of the detector is a reduction in fringe $S/N$ as overlapping photon counts from the unmodulated dimensions will dilute the fringe visibility as seen on the detector.
3.4 Image reconstruction

Reconstruction of images from the fringes follows the same procedure as for interferometric measurements in other wavebands (e.g. see 17). Each baseline samples one Fourier component of the 2-dimensional sky image of the target region, with amplitude given by the visibility, corrected for slat diffraction pattern and the fringe envelope shape. The latter will be a function of the underlying source spectrum and the instrument response (which includes detector resolution effects and weighting for effective area). The fringe phase gives the angular offset of the component in the baseline direction. The simplest way to reconstruct the image is then to take the inverse Fourier Transform of the array of amplitudes and phases from the collection of baselines.

So far, our approach has been similar to that for reconstructing images in radio and optical/IR interferometry, however it is important to note an important difference. Unlike in other wavebands, in X-rays it will be difficult to form baselines from multiple combinations of the same set of apertures (mirrors, in our case). This restriction arises due to the constrained paths that arise from using grazing incidence mirrors and the tight constraints on path length stability, which cannot easily be corrected for via a ‘delay line’ as in other wavebands. Thus for \( N \) collecting apertures, the number of independent baselines in an X-ray interferometer is likely (at least initially) limited to \( N/2 \), as opposed to \( N(N-1)/2 \) in other wavebands. For similar reasons we also cannot make use of ‘closure phase’ estimates from combinations of three apertures to calibrate out systematic phase errors between them. The lack of self-calibration of phase errors in an X-ray interferometer is already factored into the tolerances required for fringe formation and detection with a single baseline.

3.5 Simulated images for a single-spacecraft interferometer

To simulate images from an X-ray interferometer, we have adapted the Friendly Virtual Radio Interferometer software\(^*\) for use at X-ray wavelengths and angular scales and assuming only \( N/2 \) baseline pairs. The interferometer is assumed to rotate completely around the optical axis covering 12 equally spaced projection angles, to yield a total of \( N_{uv} = 6N \) distinct combinations of baseline length \( D \) and projection on the sky. The \( S/N \) for a given baseline/projection combination scales as \( \sqrt{n_{cts}/N_{uv}} \) where \( n_{cts} \) is the total number of counts forming fringes, summed over all baselines.\(^18\) A Gaussian noise correction is added to the Fourier component from each baseline/projection combination to account for observational noise, before inverting the \( uv \)-sampled Fourier transform of the sky image to obtain the simulated interferometric reconstruction.

In Figure 5 we show what is possible with a single-spacecraft interferometer observation of a nearby active star such as AU Mic, which we considered in our White Paper.\(^8\) At 10 pc, a solar radius subtends close to 1 mas at 10 pc so that a single-spacecraft interferometer with maximum baseline 1 m can resolve scales of \( \sim 100 \mu \text{as} \). We assume a central wavelength of 5 Å, with 30 geometrically spaced baseline lengths (which we also assume for the other simulations presented here). The actual number of baseline lengths can be significantly smaller than this, but the effective number is enhanced due to the broad range of resolved wavelengths contributing large numbers of X-ray counts. With \( 10^5 \) counts we can see that we resolve the stellar surface and there are possible hints of active regions and enhanced emission around the edge of the star. The structure stabilises significantly with \( 10^6 \) and \( 10^7 \) counts, so that the brightest active regions are clear and the absence of emission due to the exoplanet eclipse becomes more apparent. With typical XMM – Newton EPIC-pn count rates of tens of count/s for bright active stars such as AU Mic, such images could routinely be obtained with effective areas \( A_{\text{Eff}} > 10^3 \text{ cm}^2 \). The exoplanet transit is included to demonstrate image reconstruction, but for single spacecraft \( A_{\text{Eff}} \) it could not be resolved on a time-scale of a single transit, so that transit-phase-dependent stacking of many observations would be required to see the eclipse.

Wide orbit X-ray binary systems in our galaxy can be resolved to large distances with a single spacecraft interferometer. High mass X-ray binaries would be particularly interesting targets for exploring the interplay of accretion-powered emission with the stellar surface and wind, which could easily be resolved. Figure 6 shows a simulated image representing the nearby (\( \sim 2 \) kpc) high mass black hole X-ray binary Cygnus X-1. The direct accretion powered emission, reprocessed emission from the accretion disk rim and stellar surface and the shadow of the disk can all be seen. Not included in the simulated image, but also easily resolvable, would be emission from the surrounding powerful stellar wind which feeds the black hole. The simulation assumes \( 10^5 \) counts at 2 Å

\(^*\)Written by C. Purcell and R. Truelove and available at https://crpurcell.github.io/friendlyVRI/.
Figure 5. Original concept X-ray image of AU Mic (with transiting exoplanet) and interferometric reconstructions for \(10^5\), \(10^6\) and \(10^7\) total fringe-forming counts, assuming 30 geometrically spaced baselines with maximum baseline 1 m and average imaging wavelength 5 Å.

and so could represent an image of narrow Fe K emission which would be easy to separate from the continuum on account of its broad fringe envelope. Assuming a typical narrow line flux observed in the hard state,\(^{20}\) with an interferometer effective area of a few thousand cm\(^2\), such an image could be obtained in just 3 hours, enabling a movie of the system in Fe K emission, to be taken over its 5.6 day orbital period.

The resolution of a single-spacecraft X-ray interferometer is well matched to that of the Event Horizon Telescope (EHT) at sub-mm wavelengths which, besides its spectacular image of the supermassive black hole (SMBH) in M87,\(^1\) has also taken data from the SMBH in our own galaxy, Sgr A*. Frequent (~daily) hour-scale X-ray flaring from Sgr A* suggests that the X-rays originate from close to the SMBH. Individual moderate to bright flares (typical 2-10 keV fluence\(^{21}\) \(\sim 5 \times 10^{-9}\) erg cm\(^{-2}\) s\(^{-1}\)) are not bright enough to make an image, but given their daily rate\(^{21}\) a long observation of a couple of months would accumulate sufficient counts to make the image in Figure 7. The black hole ‘shadow’ can be seen, along with the effect of Doppler boosting on the approaching side of the accretion flow. In combination with sub-mm images taken at the same resolution, this image would also provide extremely powerful constraints on the nature of the accretion flow and emission mechanisms close to the black hole.

The sensitivity of a single-spacecraft interferometer is significantly enhanced by effective background shielding (see Section 4.5), so that targets can be studied even at cosmological distances. The image shown in Figure 8 represents the nuclear and reprocessed emission expected from an active galactic nucleus (AGN) with a pc-scale gas structure such as the molecular torus. Due to the cosmological redshift dependence of angular size, a single
Figure 6. Simulated image (right) at 2 Å that represents a 3 hour observation of the high mass black hole X-ray binary Cyg X-1 in Fe K emission only (collecting $10^5$ counts). The original image (left), showing the primary continuum source (to the right of the image), illuminated disk rim and face of the companion star (with parts shadowed by the disk) is adapted from a visualisation of a high mass X-ray binary by T. Russell and R. Hynes.

Figure 7. Simulated 2 Å interferometric image of Sgr A* (right), based on the accumulation of 50-100 X-ray flares, totalling $10^5$ counts. The simulation is based on an image of a turbulent black hole accretion disk (left). X-ray flaring is likely to be produced by synchrotron emission in the hot radiatively efficient flow, but may be Doppler boosted by rotation of the flow to produce an image similar to the one shown.

A single-spacecraft interferometer could in principle resolve pc scales across the entire visible universe, should a target be luminous enough. An image such as this could be obtained for a luminous X-ray quasar at $z = 1$ with a couple of weeks of continuous observation. A particularly interesting case would be to study the response of extended reprocessed emission in response to an AGN which may have recently flared up (e.g. due to active galactic nucleus ‘changing look’ behaviour). A single-spacecraft interferometer could monitor the response of the gas on months time-scales in order to determine the light-travel times from the nuclear continuum source to the different parts of the gas structure. By comparing this response time with the measured angular size, an accurate trigonometric measure of the Hubble constant could be obtained.

4. TECHNICAL CONSTRAINTS AND FEASIBILITY

We now consider some of the key constraints for achieving X-ray interferometric measurements from a single-spacecraft design.

4.1 Interferometer dimensions

The longest dimension of the Willingale X-ray interferometer design, $L_{\text{int}}$, is set by the length between the collector and combiner mirrors $L_{\text{coll}}$ and the total length from the combiner mirrors to the detector, $L_{\text{comb}} = L + \Delta L$:

$$L_{\text{int}} = L_{\text{coll}} + L_{\text{comb}} = \frac{D_{\text{max}}}{2 \tan(2\theta_{g,\text{max}})} + \Delta L + \left(N_f (\Delta y)^2 / \lambda\right)_{\text{max}}.$$ 

(4)
Figure 8. A pc-scale ring of reprocessed emission around a distant active galactic nucleus. Left: original image (adapted from an image of SN 1987A) and (right) simulated 2 Å image for $10^5$ photon counts imaged with 1 m maximum baselines.

The first term, $L_{\text{coll}}$, is set by the largest baseline $D_{\text{max}}$ and the corresponding mirror grazing angle $\theta_{g,\text{max}}$. Required grazing incidence angles are smaller towards shorter wavelengths, so it is likely that the longest baselines will be optimised for longer wavelengths, $\sim 10\text{Å}$ (with $\theta_g = 2^\circ$ for a range of mirror materials), while the short wavelengths (e.g. 2Å and above) required to sample Fe K emission and reflection will require $\theta_g \lesssim 0.5^\circ$, which can be provided by inner baselines with comparable resolution to the outer baselines at longer wavelengths. Advances in mirror technology (e.g. using multilayers) which can increase the grazing angles while maintaining reflectivity, can be used to reduce $L_{\text{coll}}$ or enable larger baselines to fit within the longest dimension of the spacecraft.

The separation between the combiner mirrors $\Delta L$ is required to just exceed the length of either mirror along the optical axis, and so is governed by the grazing angle and baseline beam width. Since the baseline beams are likely to be cm in scale in most $\Delta L$ should be less than 50 cm and only a few cm if the beam width is matched to the slat/gap size.

The distance $L$ from the slatted combiner mirror $M_2$ to the detector is set by a complex trade-off between the required number of fringes per slat/gap beam combination, the fringe spacing (and hence pixel size) and wavelength. At 10Å and with detector resolution $E/\Delta E \sim 10$, $L = 10$ m will allow $N_f \sim N_E = 10$ strong fringes to be detected per slat/gap beam pairing, with 34 µm fringe spacing. Comparable fringe spacing can only be maintained at shorter wavelengths by significantly reducing the slat width so that $N_f \ll N_E$, making fringe reconstruction more complex. Clearly, reducing the detector pixel size will have a large impact on reducing $L$ (or increasing $N_f$), but since fringes are produced over a considerable depth where the beams overlap, tilting of the detector plane can have a similar effect provided that the detector quantum efficiency does not suffer significantly. E.g. if the detector is tilted with respect to the fringe sampling direction by 60 degrees, the effective pixel dimension for sampling is halved and $L$ can be reduced by a factor 4.

4.2 Pathlength and pointing stability

The measurement of strong and coherent fringes requires a stable optical path difference during the measurement time. Equation (1) shows that for a fixed $y$ position on the detector, optical path difference $\Delta P$ depends on the target off-axis angle, which may vary due to instabilities in the satellite pointing. Furthermore, there may be intrinsic variations in the optical path difference due to e.g. (thermo)mechanical instabilities affecting the position or orientation of one or more mirrors, which are maximised for mirror position variations in the baseline direction. If these variations in optical path difference become large enough compared to the X-ray wavelength, the fringe phase shifts introduced will destroy the coherence and hence visibility of the fringes.

To assess the effect of optical path difference disturbances, we simulated fringes for central wavelength 10 Å, FWHM 1 Å and a 1 m baseline and added a normally-distributed random perturbation $\delta P$ to the path length
Figure 9. 1 m baseline simulated fringe visibilities for $\lambda = 10 \ \text{Å} \ (1 \ \text{Å FWHM})$ fringe envelope, using the central fringe amplitude, or that of the central 10 fringes, versus the rms amplitude of disturbances in pointing direction ($\delta \theta_{\text{rms}}$) or mirror position in the baseline direction ($\delta y_{\text{m, rms}}$).

(with rms amplitude $\delta P_{\text{rms}}$), repeating $10^5$ times to obtain the resulting average fringe pattern for a given $\delta P_{\text{rms}}$. We calculate the fringe visibility in two ways, either from the most extreme minima and maxima (arising from the central fringe) or from the fringe rms amplitude (multiplied by $\sqrt{2}$) measured over the central 10 fringes. Both measures show the same relative drop in visibility with increasing $\delta P_{\text{rms}}$, since the fringe envelope shape is not changed by the instability, only the normalisation of the fringe amplitudes. We plot the resulting evolution of visibility in Figure 9, converting $\delta P_{\text{rms}}$ to the equivalent values of pointing deviation ($\delta \theta_{\text{rms}} = \delta P_{\text{rms}}/D$) and mirror positional deviation in the baseline direction ($\delta y_{\text{m, rms}} = \delta P_{\text{rms}}/(2 \sin \theta_g)$).

The fringe visibility is reduced by $\sim 30$ per cent for pointing variations of only $30 \ \mu\text{as}$, and variations in mirror position of 2 nm. The latter requirement is not especially severe, as it lies within the present state-of-the-art for thermomechanical stability of space instrumentation as represented by Gaia which is designed for extreme thermomechanical stability (at the pico-metre level) of its defining ‘basic angle’ with its SiC construction. Continuous on-board laser interferometric measurements$^{24}$ revealed smooth, periodic (on the spacecraft rotation period) variations of a few nm along the m-scale arms of the Gaia main instrument, as well as larger drifts of tens of nm on days-weeks time-scales. These variations were later identified with perturbations due to thermoelastic coupling with heat sources on the satellite’s service module,$^{25}$ suggesting that they can be mitigated with improved thermal isolation or more careful design of the power consuming components on the spacecraft. Crucially however, the optical path perturbations observed were slow and of a scale consistent with that required for stability of detectable fringes on an X-ray interferometer. Furthermore, such effects could be significantly mitigated by accurate metrology of the baselines and optical paths of the kind used on board Gaia, since fringe locations can be accurately reconstructed if any path difference variations are precisely known.

A more challenging problem is the pointing stability, since significant jitter can be caused by mechanical vibrations linked to key spacecraft components such as gyroscopes and reaction wheels. For example, the Hubble Space Telescope still represents the state-of-the-art, with line-of-sight pointing required at the level of $< 7$ mas in a 24 hour period. Much of that jitter ($\text{rms} \sim 5$ mas) is produced on time-scales of seconds to minutes$^1$. To maintain good fringe visibility via stable pointing, we require more than two orders of magnitude improvement over these stringent constraints.

An alternative approach would be to accept a moderate level of jitter and instead attempt to measure the relative variations in pointing at the level of 30 $\mu\text{as}$ or better, using this information to correct for the jitter.

$^1$https://www.stsci.edu/itt/review/2gyro_handbook/c05_guidingjitter3.html
when reconstructing fringes (since detected X-ray photons will be tagged in time as well as location). Although
only the relative spacecraft pointing direction is needed, such measurements are also very challenging, requiring
star tracking or gyroscopes of unprecedented precision (e.g. see 11 for a detailed discussion of related issues
facing formation-flying X-ray interferometers). Thus the fringe stability due to spacecraft pointing jitter is an
area where significant progress is required before astronomical X-ray interferometry can be realised. A simple
solution would be to leverage X-ray fringe detection itself, either on shorter baselines where the tolerances are
more relaxed, or if a target is bright enough that fringes can be detected and tracked on time-scales that are
short compared to the jitter time-scale. However, either case would likely impose a significantly higher flux limit
on targets which could be imaged, compared to what would be possible with independently measured and/or
suppressed pointing jitter.

4.3 Mirror quality and effective area

Willingale14 showed that the mirror surface quality required to maintain well-defined plane wavefronts and
clean fringes is comparable to that of the best mirrors currently flying (e.g. on Chandra), with surface height
variations < 1.4 nm. Systematic variations across the mirror surface can be tens of nm (to keep fringes straight
and with constant spacing across the beam), so that existing high-quality optical flats already have sufficient
quality. Willingale et al. 26 later demonstrated a Silicon-coated slatted mirror prototype with close to the required
surface error.

A pair of interferometer arms which form a baseline will present a collecting area equal to the total projected
area of the collecting mirrors. Since the baseline beams completely overlap and the mirrors are non-focused, the
detector must present the same area as a single mirror arm in order to collect all the X-rays from both beams. As
shown in Figure 4, multiple baselines may be stacked together, with minimum spacing of 4 times the projected
mirror width, so that the total area of the collecting mirrors cannot exceed a quarter of the available area for
the spacecraft aperture. Allowing for the double reflections used to direct each beam and assuming that only
one third of X-rays are admitted by the slat/gap combination,14 the maximum effective area for a spacecraft
of aperture area \( S \) should be \( A_{\text{eff}} = \frac{1}{12} SR^2 Q \), where \( R \) is the mirror reflectivity and \( Q \) the detector quantum
efficiency for the photon energy in question.

Mirror reflectivity depends on the choice of material, photon energy and grazing angle, but for 10 Å photons
and grazing angles of 2° and < 0.5° (for the longest and shortest baselines) we would expect \( R = 0.6 \) and \( R = 0.9 \)
(for Platinum mirror surfaces1). Assuming high detector \( Q \) across the sampled energy range (e.g. > 95% for
XMM-Newton’s EPIC-pn), we expect \( A_{\text{eff}} \approx 300–600 \mbox{ cm}^2 \) per square metre of spacecraft aperture. At shorter
wavelengths, the larger grazing incidence angles required for longer baselines to fit within a 20 m long spacecraft
will not be efficient, but unlike curved focusing optics, flat mirrors with shallow grazing angles are not constrained
to small volumes by the focal length. Hence, small baselines can build up large \( A_{\text{eff}} \) at shorter wavelengths where
the angular resolution will be similar or better than that of the longest baselines and we expect the total effective
area curve of the interferometer to be rather flat versus wavelength. For a single spacecraft interferometer which
can fit inside an Ariane 6 fairing, we could expect \( A_{\text{eff}} \) up to 9000 \mbox{ cm}^2. The required detector area would be
extremely large however, at minimum 2 \mbox{ m}^2 if the detector area is optimised to match the combined beam areas
in the detector plane.

4.4 Detector design and energy resolution

Since interferometric optics are non-focused, the detector area for each baseline should match the projected area
of one of the collector mirrors for that baseline, so that large-format detectors, with high positional resolution
(ideally < 10 \mbox{ µm}) are required. For comparison with the optical band, Euclid’s VIS instrument consists of 36
CCDs each with 4096×4132 12 \mbox{ µm} pixels, for a total area of 877 \mbox{ cm}^2. The limitations of current X-ray optics do
not require astronomical X-ray detectors to have pixel sizes smaller than a few tens of \mbox{ µm}, but X-ray detectors
with \( \leq 10 \mbox{ µm} \) pixels can now be bought ‘off the shelf’, for lab-based work. Notably, the pixel dimension only
needs to be small enough to sample the fringes along the baseline direction, so that rectangular pixels can be
used to mitigate the requirements for giga-pixel arrays to cover areas > 1000 \mbox{ cm}^2.

1https://henke.lbl.gov/optical_constants/mirror2.html
Increasing the detector energy resolution proportionately increases the longitudinal coherence length at a sampled continuum wavelength, enabling more fringes to be sampled across a combined baseline beam, which has strong beneficial effects in increasing the Field of View, as described in Section 3.2. Current CCD detectors allow \( N_E \sim 10 \) strong fringes to be sampled at 10 Å and up to \( \sim 50 \) at 2 Å, so that \( S/N \) for fringe detection is optimised for beams of this width, i.e. with \( \text{FoV} \sim 10 - 50 \) times the interferometric resolution for a given baseline. Larger energy resolutions, approaching those of X-ray calorimeters, would enable much larger fields of view (exceeding 1000 resolution elements) to be efficiently imaged, significantly relaxing the tolerance for systematic errors in optical paths or due to spacecraft pointing. However, building such detectors with sufficiently large area for X-ray interferometry will be very challenging. New approaches may be required that consider e.g. the relaxation of requirements for square pixels as well as the reduced photon count rates expected due to the non-focusing nature of the optics.

4.5 Stray light and background

The non-focusing nature of interferometric optics means that the density of source photons on the detector is very low compared to conventional X-ray imaging instruments. Therefore, it is important to consider how to mitigate the effect on the interferometric \( S/N \) of stray light (in this case, X-rays from outside the interferometrically imaged region) as well as the non-X-ray background (particle or high-energy off-axis photons). Here, the non-focusing nature of the optics comes to our aid, because the X-rays arriving at each point on the detector can be restricted to a narrow range of paths, corresponding to the beams formed by each interferometer arm. This means that collimation can be extremely effective for removing stray light and background, using a collimator designed to admit only each baseline beam and which could be placed between the collector and combiner mirrors, or between the combiner mirrors and the detector.

Such a collimator would possess rectangular apertures and primarily prevent entry of photons/particles with offsets along the baseline direction of less than 1 arcminute (corresponding to the baseline beam width at \( L \)). Together with less restrictive collimation in the perpendicular direction, stray light would be effectively removed. Particle and off-axis hard-X-ray/\( \gamma \)-radiation can be removed if lead glass is used for the collimator and lead back shielding is placed behind the detector. Similar shielding is proposed for the Large Area Detector (LAD) on board the \( eXTP \) mission, which reduces the particle background so that the expected background rate per cm\(^2\), assuming operation at L2 for thermal stability reasons, would be two orders of magnitude lower than that of \( Athena \)'s WFI instrument at the same location, enabling targets with 2-10 keV flux below \( 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) to be imaged interferometrically.

5. CONCLUSIONS

We have demonstrated that single-spacecraft interferometry is technically feasible. A certain amount of development is required, combining existing technologies and capabilities to make a start on realising its remarkable potential. In a separate paper in these proceedings by R. den Hartog et al., we consider the required thermo-mechanical tolerances and other aspects in more detail along with an approach for realising X-ray interferometry ‘in the lab’ up to the required 10 cm and 1 m scales, using a testbed to be operated at a synchrotron source or a long X-ray beamline. Once this has been achieved, work can begin towards qualification and use in space. Particular focus will be needed on the development of large-format, small-pixel detectors and the stabilisation of fringes in response to spacecraft jitter.

Thanks to the scalability of the interferometer optics, it is theoretically possible for a much smaller instrument than discussed here, e.g. with 10 cm maximum baselines and \( \sim 1 \) mas resolution, to be flown on a 1 m scale spacecraft (i.e. a smallsat) as a possible intermediate step to the large mission envisaged here. A smallsat mission would be challenged by the pointing stability requirements for X-ray interferometry, but could potentially be feasible for bright galactic sources (for which fringes can be detected and tracked in real time) and besides the more limited imaging, could obtain very interesting results using differential astrometry, which can be obtained with positional resolution \( \sim \theta_r / \sqrt{N_{\text{fr.}}} \).

In the longer term, beyond the flight of a large single-spacecraft interferometer, we expect continuous improvements in formation-flying techniques and technology, which will eventually make possible a much larger array of X-ray collector and detector spacecraft, to form a constellation X-ray interferometer. The compact
Willingale design can easily be extended to such a configuration, if the combiner mirrors are flown on the same spacecraft as the detector. For example, 1 km baselines with 20 km collector and combiner/detector separations can be achieved with-sub µas resolution, to image the event horizons of the supermassive black holes in many AGN, as envisaged by the original NASA concept studies. Single-spacecraft X-ray interferometers will form an essential step to that destination, to hone the technology and techniques as well as providing inspirational and breakthrough science to point the way to the long-term goal, of completely removing the constraints on X-ray angular resolution.

REFERENCES


