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ABSTRACT

Compact sources of 14-MeV neutrons have been imaged with a penumbral-coded aperture at a two-point resolution of 80 µm. We desire to improve the penumbral-aperture microscope to obtain resolutions as fine as 10 µm. In penumbral-coded-aperture imaging, the resolution is ultimately limited by the sharpness of the aperture point-spread function. I present a design for a thick penumbral aperture that provides the desired sharpness over a field of view of 150 µm. The point-spread function of these apertures is sufficiently isoplanatic and distortion-free to allow linear reconstruction of complex source distributions. The design is generally appropriate for similar imaging techniques, such as fine-resolution neutron or gamma-ray pinhole imaging.

INTRODUCTION

Neutron penumbral-aperture imaging is used to obtain information on the spatial extent of fusion reactions in the imploded core of inertial-confinement fusion targets. This method has been used[1] to obtain neutron images at a two-point resolution of 80 µm over a 400-µm field of view. We wish to increase the two-point resolution to 10 µm over a field of view of at least 100 µm.

In penumbral imaging, the spatial resolution is ultimately limited by the sharpness of the aperture point-spread function (PSF). The thick-aperture design described here provides <10 µm resolution over a field of view of 150 µm. The aperture PSF is sufficiently isoplanatic and distortion-free across the field of view to allow the use of linear reconstruction methods in unfolding the penumbral-coded images. The design is generally applicable to other imaging techniques that require an aperture whose diameter is much smaller than its thickness.

Simple conical apertures[2,3] have an acceptably sharp PSF when the desired field of view is much smaller than the aperture diameter. The resolution available with such apertures suffers if (as is generally the case) they must be detuned (by moving the vertex of the cone away from the source plane) to provide acceptable isoplanaticity. Improved performance is available with apertures having a parabolic taper,[1,4] but the resolution achievable with such designs appears to be no better than 15 µm.

The principle of the thick-aperture taper is based on simple geometric considerations. A PSF is determined by the amount of aperture material intersected by each ray from a particular source point; that amount varies with the angular displacement of the ray. For small displacements, a cylindrically symmetric aperture becomes isoplanatic when the radius of curvature of the aperture taper varies inversely with distance from the source plane; this provides a differential equation that partially determines the taper function. Sharpness is optimized by forcing the tangents at the ends of the taper to point at the edges of the field of view; this condition completes the specification of the taper function. The aperture is uniquely determined by specifying field of view, initial aperture radius, aperture thickness, and distance from the source plane to the front face of the aperture. The differential equation is solved numerically to generate the aperture profile.

Below, the characteristics of a sample PSF obtained with such a taper are examined in detail. Images from point sources are created by tracing rays through the aperture. The noise-free images are deconvolved with a Wiener filter to determine the effective resolution in the source plane. Resolutions of <10 µm can be obtained. Use of the on-axis PSF to unfold the images of off-axis point sources provides a measure of the distortion due to anisoplanaticity. Resolution deteriorates somewhat as the source point moves away from the axis; substantial deterioration is common at the edge of the field of view. Magnification also varies with radial displacement of the image, typically increasing by 5 to 10% between the axis and the edge of the field of view.

PRINCIPLE OF OPERATION

The PSF of a cylindrically symmetric aperture can be examined in a two-dimensional (ρ, z) geometry. Consider the intersection of a ray emanating at angle θ from a source point with a circle of radius R centered at the origin of the coordinate system (Fig. 1). To determine the intersection points, we must solve the equations

$$\left\{ \begin{matrix} \rho - R = \theta(z - z_i) \\ \rho^2 + z^2 = R^2 \end{matrix} \right\}, \tag{1}$$

where z_i is the distance between the source and the aperture at the point of first intersection (tangency). The system is easily solved to give the path length Δz through the circle as

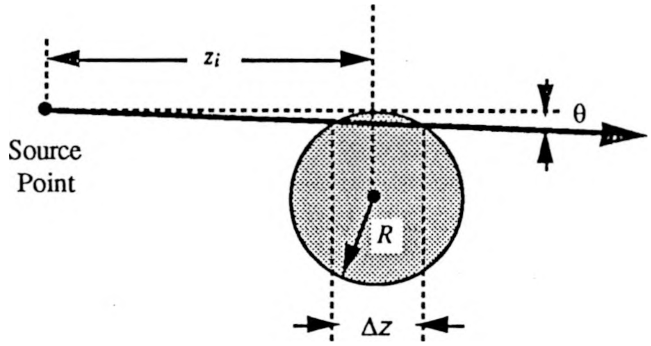

Fig. 1. Geometry of the theoretical development. A ray from a source point cuts a circle of radius *R*.

$$\Delta z \cong 2R\,(1-q)\sqrt{\theta^2 + \frac{1}{(1-q)^2} - 1}\,, \qquad (2)$$

where we have assumed that $\theta \ll 1$. In addition we have $q \equiv l\,\theta/R \ll 1$ for $z < R$, which is almost always the case of interest. To first order in q, we then have the further approximation

$$\Delta z \cong 2R\,\sqrt{\theta^2 + 2q}\,. \qquad (3)$$

The θ^2 term is independent of the source–aperture distance l; the $2q$ term is proportional to $R^2 q = lR\theta$. Now take R as the radius of curvature of a tapered cylindrical aperture. Rays from different source points in the aperture field of view will intersect the aperture with different values of $l \propto z$. If $R \propto 1/z$, then Δz will be independent of l, and the requirement

$$R = \frac{z_0}{z} R_0 \qquad (4)$$

yields a differential equation for $\rho(z)$ that defines a particularly isoplanatic taper. In Eq. (4), R_0 is the initial radius of curvature at the front face of the aperture that is separated from the source by a distance z_0.

Determination of the taper requires solution of the second-order nonlinear ordinary differential equation

$$\frac{d^2\rho}{dz^2} = \frac{z}{z_0 R_0}\left[1 + \left(\frac{d\rho}{dz}\right)^2\right]. \qquad (5)$$

Equation (5) can be written as a pair of coupled first-order differential equations and solved by standard numerical methods. The initial aperture diameter, slope ($d\rho/dz$), and radius of curvature must be specified along with the source–aperture separation; the set is then solved to obtain an aperture of some desired length. To maximize the sharpness of the aperture PSF, the initial and final slopes must be chosen to define the geometric field of view (Fig. 2). The initial radius of curvature determines how rapidly the aperture flares outward, and R_0 is chosen so that the radius and slope of the aperture at its exit define the outer extremity of the field of view. By iterating the initial-value problem, we obtain the aperture taper from a specification of source–aperture distance, initial aperture diameter, and geometric field of view. The aperture taper will hereafter be termed *inversely varying radius of curvature* (IRC).

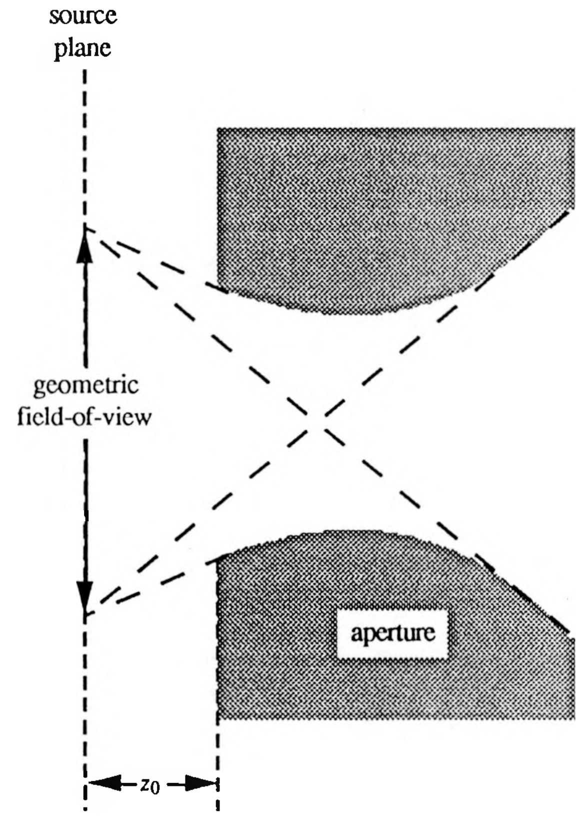

Fig. 2. Lines drawn tangent to the entrance and exit surfaces of the aperture define the geometric field of view.

IRC Aperture Point-Spread Response

An example of the IRC aperture will be analyzed in detail. Given design constraints appropriate to the Nova laser facility, an aperture taper is chosen. Then the resolution, isoplanaticity, and magnification of the thick penumbral-aperture system are described.

To obtain maximum signal in the image we must minimize the source–aperture distance, so we take $z_0 = 2$ cm. The instrument should have a two-point resolution of <10 μm and a useful field of view of 100 to 150 μm. Below it is shown that blurring towards the edge of the geometric field of view requires the selection of an oversize region, here 240 μm. Using the IRC design for a 6-cm-thick gold aperture with a minimum diameter of 175 μm, we obtain the taper function shown in Fig, 3(a); the corresponding PSF is plotted in Fig. 3(b). (Use of an aperture with a much larger diameter

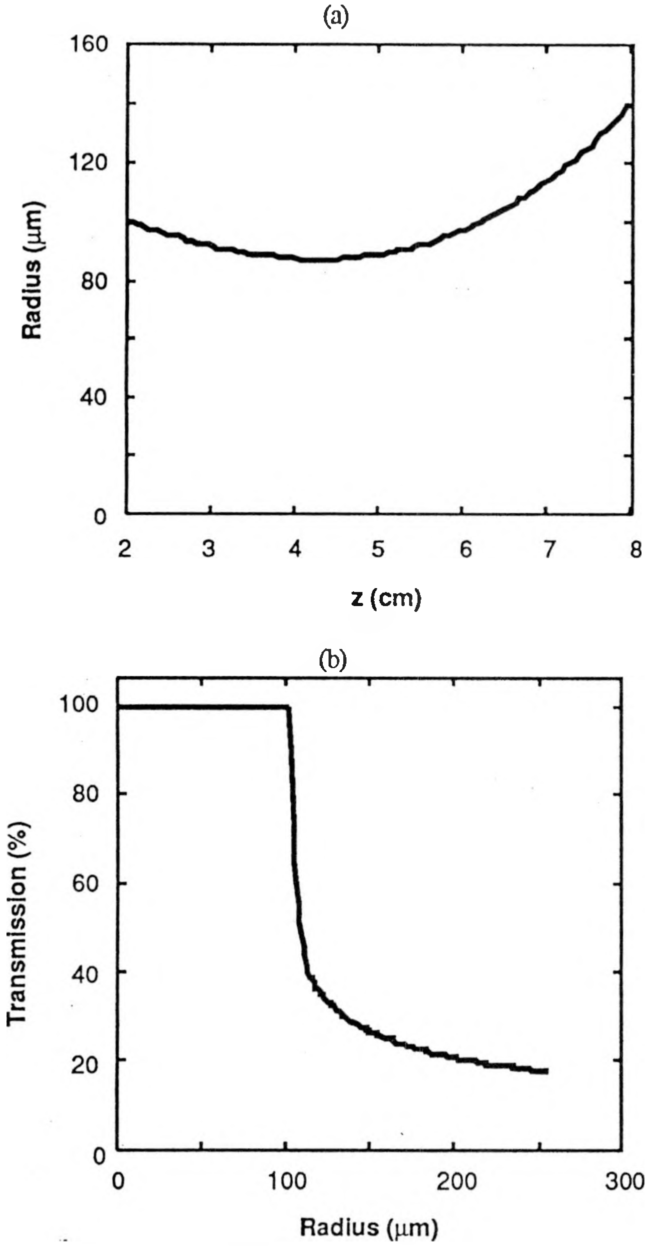

Fig. 3. IRC design for a neutron penumbral-aperture microscope: (a) taper function; (b) point-spread function.

would improve the image signal-to-noise ratio; the small aperture was used here to simplify the computational requirements of the immediate analysis. Similar results can be obtained with aperture diameters as large as 1 mm.) The aperture has a relatively linear taper (large radius of curvature) near the entrance, then flares increasingly towards the exit; this is a fundamental characteristic of the design. The aperture initially tapers inward, because (in this case) the geometric field of view is larger than the entrance diameter.

Figure 4 shows the resolution and isoplanaticity of the aperture. The resolution of a penumbral aperture is determined by the sharpness of the cutoff at the edge of the aperture. Image formation with an IRC aperture was simulated by tracing rays from specific source points through the aperture. The transmission was recorded on a fine grid corresponding to a 1-μm pixel width in the source plane. Figure 4(a) shows the aperture cutoffs of on-axis and 50-μm-displaced source points; the x-axis scaling has been referred to the source plane by dividing by $1 + M$, where M is the magnification of the system (defined below). The initial sharp portion of the cutoff is quite isoplanatic, as desired, but the displaced source point generates a different "tail" in the image.

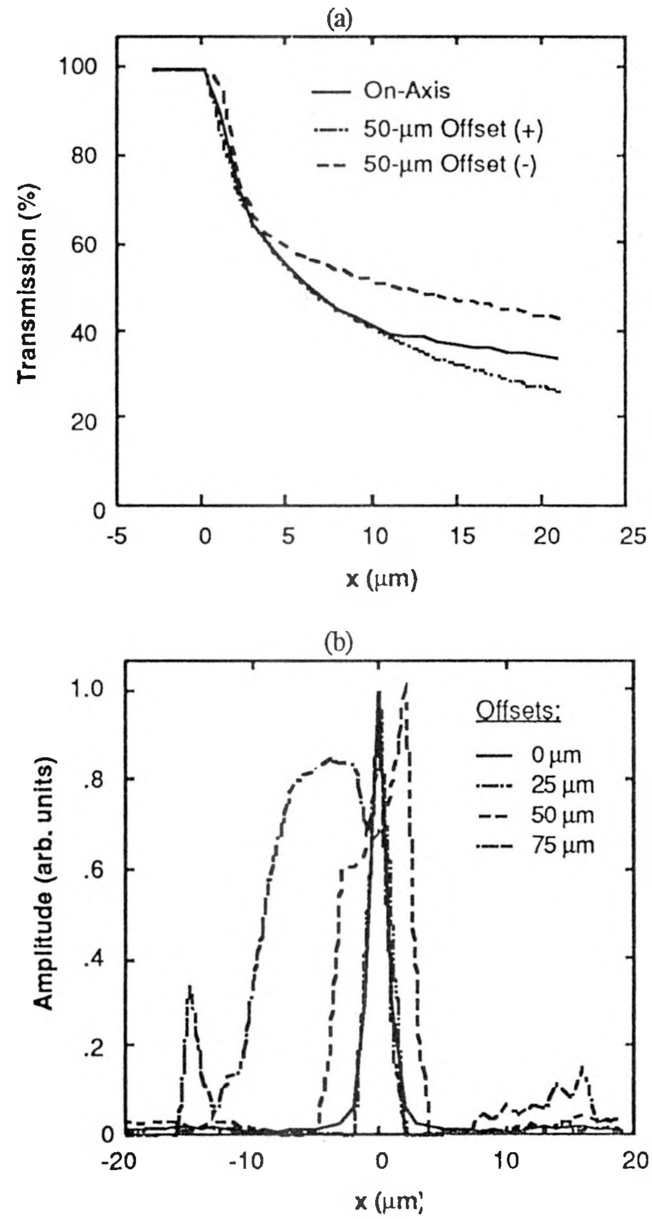

Fig. 4. Resolution and isoplanaticity of the IRC aperture: (a) detail of the PSF cutoff; (b) deconvolved resolution functions for various source-point offsets. The resolution functions have been normalized to unity.

It is also desirable to examine the resolution of the aperture after deconvolution. Here, we carry out the deconvolution with a parametric Wiener filter defined in the Fourier transform domain,

$$\frac{1}{A_{ref}}\left[\frac{1}{1 + k / |A_{ref}|^2}\right], \qquad (6)$$

where A_{ref} is (the transform of) an idealized penumbral-aperture PSF, specifically the rectangle function $\Pi(\rho/D)$ defined by Bracewell,[5] with a diameter equal to that of the IRC on-axis PSF. The parameter k is kept very small (10^{-4}) for these noise-free images, but it must be nonzero to remove significant numerical errors that develop near the zeroes of A_{ref}.

Figure 4(b) shows the resulting reconstructed point-spread or resolution functions for on-axis and displaced point sources. Small offsets cause virtually no distortion, and the resolution is excellent; the FWHM for both on-axis points and points displaced 25 µm is <2 µm. Broadening and some distortion are visible at a 50-µm offset: the FWHM has risen to 5.3 µm, and a double peak is visible. At an offset of 75 µm the FWHM has risen to 10.3 µm. Thus, to obtain a two-point resolution of 10 µm, the effective field of view of this aperture must be restricted to 150 µm; points outside of this range will be blurred more than desired. The FWHM of the resolution function is plotted as a function of radius in Fig. 5.

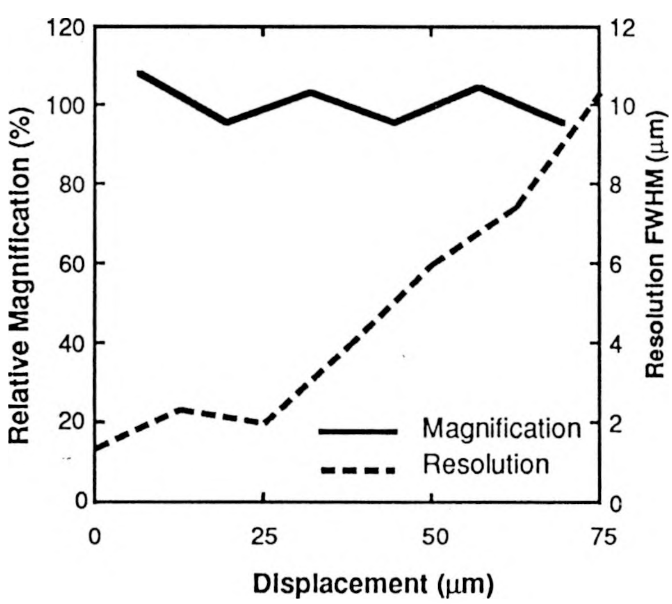

Fig. 5. Magnification and resolution of the example IRC aperture vs radial displacement in the source plane. Although the resolution deteriorates with increasing radius, the magnification remains approximately constant.

CONCLUSIONS

Like the resolution, it is easiest and most intuitive to define the magnification of the imaging system with respect to the reconstructed resolution functions. We therefore define the magnification as the ratio of the change in the centroid of the resolution function to the corresponding change in the source-point position. For the example IRC aperture, the magnification (Fig. 5) is constant to ±5% within the 150-µm useful field of view. The IRC aperture therefore produces no geometric distortion in the image, at least with respect to its first-order moment. (Higher order distortions are present, however.)

A thick-aperture design for high-resolution imaging of penetrating radiation has been presented. The design is based on a simple analysis of the intersection of rays emanating from a source region with a circle; the analysis is generalized through the use of a differential equation involving the radius of curvature of a cylindrically symmetric aperture. The radius of curvature of the resulting taper varies inversely with the corresponding separation from the source point.

The aperture design has immediate application in a planned neutron penumbral-aperture microscope at the Nova laser facility. A hypothetical aperture design for such an instrument was shown to provide at least 10-µm resolution over a 150-µm field of view with no significant first-order distortion.

The IRC aperture design presented here may also be useful in other imaging systems. In particular, the design could be optimal for use in thick-pinhole imaging systems where a small-diameter aperture must view a relatively large field of view at a small source-aperture distance.

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