Fresnel Zone Plate Telescopes as high resolution imaging devices

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Abstract—Combination of Fresnel Zone Plates (FZP) can make excellent telescopes for imaging in X-rays. We present the results of our experiments with such telescopes with an X-ray source kept at a distance of 45 feet. We compare the patterns obtained from experiments with those obtained by our Monte-Carlo simulations. In simulations, we allow the sources to be at finite distances (diverging beam) as well as at infinite distances (parallel beam) and show that the resolution is worsened when the source is nearby. We also present simulated results for the observation of the galactic center and show that the sources may be reconstructed with accuracy. We compare the performance of such a telescope with other X-ray imaging devices used in space-astronomy. The Zone Plate based instrument has been sent for the first time in a recently launched KORONAS-FOTON satellite.

I. INTRODUCTION

Zone Plate Telescopes (ZPTs) have generated immense theoretical interest [1-7]. In Chakrabarti et al. [8] and Palit et al. [9], extensive theoretical studies have been presented and some of the results of the experiments on such telescopes conducted at the Indian Centre for Space Physics X-ray laboratory. Such telescopes have already been used in RT-2 Payloads aboard Russian satellite KORONAS-FOTON launched on 30th January, 2009. The ZPTs have an advantage over other high resolution X-ray telescopes [10-11] in that they can have arbitrarily high angular resolution and that the resolution can also be independent of energy bands in a large range of energy. The only disadvantage is that ZPTs are two-element systems as opposed to the conventional coded aperture masks (CAMs) which are single element systems. In a zone plate telescope, two plates are aligned but the source is kept off-axis in order to get relative shift of the ray of light on the image plane. Sources at higher off-axis locations produce finer fringe separations. These fringes may or may not be separable depending on how fine the detector pixels are. The fringe patterns on the detector are inverse Fourier transformed to get the source location.

II. EXPERIMENTAL SETUP, MONTE-CARLO SIMULATIONS AND THE COMPARISON OF THE RESULTS

Fig. 1a shows our experimental setup. It consists of an X-ray generator with a molybdenum target. The beam line is 45 feet long. The anode voltage and the current can be controlled at will. At the end of the beam-line, the tungsten zone plates (Fig. 1b) are placed which are followed by a CMOS detector having the pixel size equal to 50 micron. The zone plates we use are made up of 1 mm thick tungsten, the ‘opaque’ zones are opaque up to ~ 100keV. We did not choose to vacuum the beam-line and supply high energy X-rays by applying higher anode voltage instead. The intervening air column will cause an absorption in the soft X-rays but hard X-rays including the Kα and Kβ lines will remain strong.

Fig. 1: (a) The 45 feet beam-line used in our experiments. At the near end is the X-ray generator (0-50kV) with molybdenum target and at the far end is the detector assembly. (b) A positive zone plate. [8]
Monte-Carlo simulations are done to reproduce circumstances when it is difficult to change the experimental set-up at will. We conduct simulations not only to reproduce the cases when experiments were carried out, but also by placing the detector at different distances, and with arbitrarily high or low photon fluxes. We also conduct simulations with multiple sources. The code was written in IDL details are in [8-9].

Fig. 2a shows the shadow cast by two aligned zone plates when the source is almost on the axis of the plate holder. The circular fringes are of diameter \( r_{d,m} = r_1 \left( \frac{2(2m-1)}{D(1-D^2)} \right)^{1/2} \), where \( r_1 \) is the radius of the central zone, \( z \) is the distance of the source from the first zone plate (facing the source), \( D \) is the distance between the zone plates and \( m \) is the dark fringe number from the center. In our case, \( r_1 = 0.122 \) cm, \( D = 20 \) cm, \( z = 1338 \) cm. In Fig. 2b, we show the results of the simulation. Reconstructed image shows sharp rise of counts at the center.

Fig. 3: Fringe patterns from the (a) experiment and the (b) simulation when the zone plates are placed at a distance of \( D = 20 \) cm and the source is 0.65 degree away from the optical axis. \( 5 \times 10^6 \) photons were used in the simulation. The deconvolved images from (a) and (b) are drawn in (c) and (d) respectively. The image becomes sharper as the source is taken farther out [8].

Figs. 3(a-b) show the fringes produced on the detector plane by a misaligned source: (a) is the actual experimental result on a CMOS detector and (b) is the simulation result. In Figs. 3(c-d), the reconstructed images are shown. Since we used only one pair of zone plates, both the central DC offset as well as the alias (mirror image) are seen. These would be removed by using four pairs of zone plates as shown below.

First, we present the results of simulations with the source placed at infinity. The zone plate spacing in each case is taken to be 10 cm. The source is placed at an angular distance of \( \phi = 1500 \) arcsec from the optical axis and at a zenith angle of \( \theta = 45 \) degree measured from the positive X-axis. The number of photons infalling on each of the front zone plates (ZP1s) is \( 10^5 \). The fringes obtained in each of the pairs is given in Fig. 4a. The source obtained by reconstruction is shown in Fig. 4b. Neither the DC offset, nor the pseudo-source appears in the reconstructed image.

When the source is at a finite distance, the DC off-set is always canceled but the pseudo-source cannot be canceled even if four pairs are used. This is because the angles subtended by the source at different pairs are different. For point sources at finite distances, when reconstructed from the fringe pattern, there are spreads. These are due to the point spread function, which assumes the shape of the aperture of imaging device (here the common area of the two zone plates intersected by the rays coming from the sources). This broadening worsens angular resolution for nearby sources.

To show this effect prominently we carry out the following simulation with two sources. One is placed at \( \phi = 2400 \) arcsec and \( \theta = 0 \) degree and the other is placed at \( \phi = 1200 \) arcsec and \( \theta = 90 \) degree. The sources are placed at a distance of 45 ft from ZP1. The zone plate separation is taken to be 100 cm. In Fig. 5a, we show the fringe pattern and in Fig. 5b, we show the reconstructed image (5800 arcsec on each side). It is clear that locationwise, the sources have been placed properly, although they look ‘similar’ to the Moiré fringe patterns, which have special shapes due to off-axisness of the sources. In the simulations, the number of photons impinging from these two sources are taken to be 100000 and 70000 respectively, causing
Fig. 4: (a) Fringes obtained for a source at an infinite distance with four pairs of zone plates. (b) Reconstructed source on a CMOS detector (4500 arcsec along each side of the squared base. Neither the pseudo-source nor the DC offset are seen in the reconstructed image [9].

one pattern to be slightly brighter than the other.

In order to demonstrate the capability of resolution of a ZPT, in Figs. 6(a-b), we show the reconstructed images of a pair of sources which were placed at an angular distance of (a) 103 arcsec and (b) 51.5 arcsec (limiting case). Each side of the base is 20 arcmin in length. This agrees with the resolution of the instrument $\theta = 2\delta r / D$, where $\delta r$ is width of the finest ring of the zone plate and $D$ is the zone plate separation. In our case, $\delta r = 50\text{micron}$ and $D = 40\text{cm}$ and hence the resolution is 51.5 arcsec.

Fig. 5: (a) Moiré fringe patterns obtained for two sources placed at about 45 ft away from the front zone plate. In the telescope, the plates are separated by 100 cm. (b) The reconstructed images. Due to large off-axisness the fringes do not cover the entire zone plates. The image size is compatible with the distance of the source and the image shape is compatible with the degree off-axisness.

Fig. 6: Sources placed at infinity and separated by (a) 103 arcsec and (b) 51.5 arcsec respectively are reconstructed from the fringe patterns. The zone plate separation is 40 cm. In each Figure, the base is 20 arcmin on each side [9].
We now present the result of the simulation in which we examine how the fringe system should look like when a prominent X-ray sources are turned on near the Galactic center. In Fig. 7a, we show the fringe patterns produced by the four pairs of zone plates on a CMOS detector (50 micron pixel size). The plate separation is 20 cm. The reconstructed source distribution is seen in Fig. 7b.

III. CONCLUDING REMARKS

With the technological advancements it has become possible to produce very accurate large area zone plates having very fine rings using very heavy metals such as tungstens. We presented results using pairs of tungsten zone plates which are of ~ 3.0cm diameter and show that achromatic angular resolution of a few tens of arc seconds was possible even when the plate separation is only tens of centimeters. By increasing the separation of the zone plates, it is possible to obtain arbitrarily high resolutions. With four pairs of zone plates (two for sine and two for cosine transforms), very accurate imaging is possible. However, the ultimate result depends on the type of the detector placed behind the telescope. In a CMOS detector, the information about energy is lost. In a CZT type detector, the energy dependent imaging is possible, but the image resolution is compromised since the pixel size is 50 times bigger that that of CMOS.

Because the size of the zone plates having finer zones can be at the most a few cm, imaging faint sources would be impossible. Thus zone plates are most suited for transient bright and pointlike sources. In the Russian solar mission named KORONAS-FOTON which was launched on the 30th January, 2009, the zone plate set-up mentioned above is included in the Indian payload RT-2/CZT. The sun is still in the quiet phase and images can be obtained when it is more active.

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REFERENCES

[1] L. Mertz, & N.O. Young, Fresnel Transformation of Images, Proc. Int. Conf. on Opt. Instrum. Techniques, ed. K.J. Habell (London: Chapman and Hall), 305, 1961
[2] J.G. Ables, Fourier transform photography: a new method for X-ray astronomy, Proc. Astron. Soc. Australia, 1, 172, 1968
[3] R.H. Dicke, Scatter hole cameras for X-ray and gamma-rays, ApJ, 153, L101, 1968
[4] H.H. Barrett and W. Swindell Radiological Imaging: Theory of Image Formation, Detection and Processing, Vols. I and II, Academic Press, New York, 1996
[5] U.D. Desai, J.P. Norris and R.J. Nemiroff, in Astroparticle Physics and Novel Gamma-Ray Telescopes, SPIE, 1948, 75 (1993)
[6] U. Desai, L.E. Orwig, L. Fiquet and C.C. Gaither, “X-ray telescope for small satellites,” Proc. SPIE Vol. 3442, p.94, Missions to the Sun II, Ed. C.M. Korendyke (1998)
[7] U. Desai, L. E. Orwig, Mertz, L., Gaither, C.C.III and W. Gibson, “Shadow Mask Telescope for High Energy X-rays,” in High Energy Solar Physics: Anticipating HESSI, Vol. 206, p. 284, Eds. R. Ramaty & N. Mandzhavidze, ASP (San Francisco) (2000)
[8] S.K. Chakrabarti, S. Palit, D. Debnath, A. Nandi, V. Yadav and R. Sarkar, “Fresnel zone plate telescope for X-ray imaging I: experiments with a quasi-parallel beam”, Exp. Astron., 24, 109, 2009.
[9] S. Palit, S.K. Chakrabarti, D. Debnath, A. Rao, A. Nandi, V. Yadav, V. Girish, Exp. Astron. (submitted), 2009
[10] B.D. Ramsey, Advances in Space Research, 38, 2985, 2006
[11] G. Pereschi, Mem. D. Soc. It., 79, 26, 2008