

Comparing Wide Field Optical Designs for X-ray Counterpart of Gravitational Wave Events Search

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ABSTRACT

Gravitational wave observatories localize sources only in a small area of the sky that, also for future detectors, will be of $\sim 10\text{--}100\text{ deg}^2$. Current X-ray telescopes are incapable of quickly localizing the X-ray source in that area, because they either have a very small field of view – so incapable of scanning that area in a short period of time – or are wide-field monitors – but with inadequate sensitivity. This capability however will become increasingly important when the current gravitational wave experiments (LIGO and Virgo) will work at full sensitivity, or when the future experiments – Einstein Telescope observatory, the Cosmic Explorer and the space mission LISA – will come online in the next decades. In this contribution we compare the optical designs capable of following up gravitational wave events in X-rays — Wolter-I, Kirkpatrick-Baez and Lobster eye. We set as scientific requirement a source localization accuracy of tens of arcsec over a 10 square degrees field of view, together with hundreds of cm^2 effective area. We compare the advantages and drawbacks of each optical design regarding the effective area, angular resolution and field of view.

Keywords: X-ray astronomical optics – Wolter-I optics – Lobster Eye – Kirkpatrick-Baez – Wide field optics – Gravitational wave electromagnetic counterparts

1. INTRODUCTION

Gravitational wave detections have recently opened a new window on the Universe, and the next decades will see a great expansion of these detections, thanks to the 3rd-generation Einstein Telescope¹ and Cosmic Explorer,² and in space also thanks to the Laser Interferometer Space Antenna (LISA³).

However, not only for present gravitational waves detectors but also for the future ones, the localization of the gravitational wave event is in a large region of the sky, of the order of $10\text{--}100\text{ deg}^2$. A telescope looking for the electromagnetic counterpart therefore needs to be able to observe a region of the sky of this size quickly, with just a few repointings.

If we look at the X-ray band in particular, we find that current telescopes are either narrow-field instruments — dedicated to studying in great detail one source at a time — or all-sky monitors — having a field of view much larger, and not sufficient localization sensitivity, with respect to what is needed to find electromagnetic counterparts of gravitational wave events. With the goal of building a middle ground between these two extremes, but also capable of fitting in the payload of a small mission, in this work we compare the capabilities of the possible different X-ray optical designs that could be used for this scientific goal. The scientific mission requirements we set as goal are reported in table 1

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Field of view	$>10 \text{ deg}^2 = 1.8 \text{ deg radius}$
Effective Area	$>100 \text{ cm}^2$ over the field
Half Energy Width	$<200 \text{ arcsec}$ over the field

Table 1. Mission requirements used in this paper for a mission dedicated to accurately localizing gravitational wave events electromagnetic counterparts.⁴

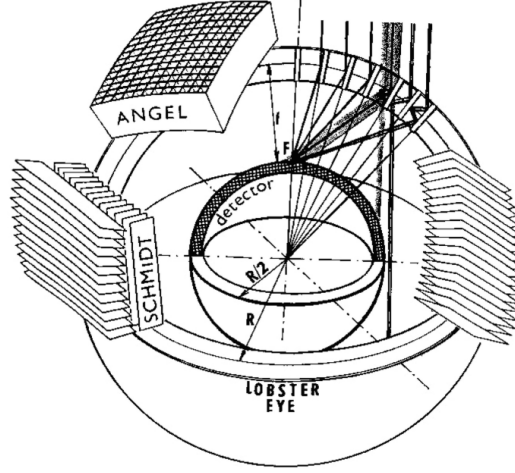


Figure 1. Drawing showing how Lobster eye telescopes function, in both the Angel⁵ and Schmidt⁶ variants.⁷

2. LOBSTER EYES AND KIRKPATRICK-BAEZ DESIGNS

One optical design that finds applications in X-ray astronomy is the Lobster eye: inspired by the eyes of crustaceans, these optics are based on double reflections on orthogonal flat mirrors; two designs have been proposed, named Angel and Schmidt after their proposers.

The Angel design⁵ is made of square capillary tubes that have a length much greater than their width, so grazing incidence occurs (figure 1). The rays focus at a distance equal to half the radius of curvature of the spherical surface over which the capillary tubes are distributed. The field of view depends on how wide the portion of this sphere is (i.e. how many capillaries there are), while the angular resolution depends on the radius of curvature (and therefore on the focal length) and on the width of the capillaries. The Lobster-Schmidt⁶ design operates on similar principles but utilizes two arrays of flat mirrors at different curvature radii, so the two orthogonal reflecting surfaces are shifted.

The point spread function of these systems is peculiar compared to Wolter-I systems: some photons pass through without impacting any mirror, forming a diffuse background, some photons reflect on two orthogonal mirrors, forming a focused point, but some photons only reflect on one mirror and, depending on which mirror, form two arms of a cross-shaped point spread function. This implies that for these systems, the localization information is contained not only in the central focusing point, but also in this “cross” shape. The effective area is then computed using all photons that focus in the center and in the cross, and also the half energy width is computed using the thickness of the cross in the x and y projections, so taking into account the peculiar shape of the point spread function.

Some X-ray wide field monitors have been built based on the Lobster eye design. There is one such telescope on-board the Lobster-Eye X-ray Satellite⁸ and on-board the Einstein probe mission;⁹ both of these have a very wide field of view (3600 deg^2 for the Einstein probe), but modest angular resolution (5 arcmin for the Einstein probe). Another Lobster eye is present on-board the SVOM mission (Space-based multi-band astronomical Variable Objects Monitor¹⁰), with a smaller field of view ($58 \times 58 \text{ arcmin}^2$) but still modest angular resolution ($\lesssim 2 \text{ arcmin}$).

Another alternative design to Wolter-I optics is the Kirkpatrick-Baez¹¹ built very similar to Lobster-Schmidt design, but made of parabolic instead of flat mirrors. For more details on the ray-tracing simulations of these designs, see Ref. 12.

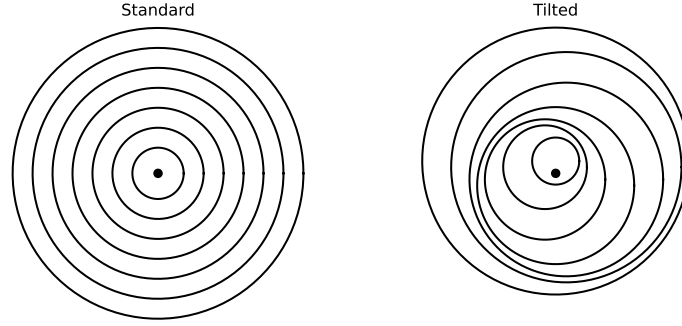


Figure 2. Example of standard (left) and tilted (right) Wolter-I shells seen from above the telescope.⁴

3. TILTED WOLTER-I DESIGN

The most commonly used optical design in X-ray astronomy is the Wolter-I: based on grazing incidence double reflection on two surfaces, one parabolic and one hyperbolic. To increase the effective area, these systems are commonly made of many confocal shells, which are aligned so to maximize the performance on-axis.

Ref. 4 describes instead a variant in which the different shells are tilted in different directions (figure 2), this way increasing the field of view at the cost of a worsening of the on-axis performance. The length of the shells and the focal distance are also optimized to improve the overall performance of the entire field of view at the cost of the on-axis performance.

Ref. 4 presents the design for a module that uses the same radii (but different lengths) as the shells of eROSITA,¹³ so allowing to reuse its mandrels, this way making the manufacturing process greatly faster and cheaper.

4. COMPARISON OF THE DIFFERENT X-RAY OPTICAL DESIGNS

Figure 3 shows a comparison of the different optical designs:

- Lobster eye in the Angel variant (the Schmidt variant⁶ gives the same results)
- Kirkpatrick-Baez
- Standard (non-tilted) Wolter-I design
- Tilted Wolter-I design

The comparison is done at a focal length of 2000 mm for all designs. The same overall volume of mirror material is taken for the different designs (which would translate to the same mass assuming the same material and manufacturing process). These factors imply that, while the length of the optical system is the same given a focal length, the width can differ.

The other geometrical parameters are however different for the different designs, which have a different optimal configuration (see Ref. 12): the mirror lengths of the Lobster–Angel, Lobster–Schmidt and Kirkpatrick–Baez are of 40 mm each. For these designs, the mirror thickness is 0.35 mm and the mirror separation is 0.75 mm. Keeping the same mirror material as the Wolter-I systems considered in this paper implies a size for Lobster and Kirkpatrick–Baez systems smaller than for Wolter-I systems, of 300 mm×300 mm (corresponding to 275 layers on each side). All these values translate into both a different filling factor and a different geometric area for the different designs, and so in different effective areas on-axis. Table 2 summarizes the optical parameters in common, and differing, between the designs we are comparing.

Some results worth of notice from figure 3 are:

	Lobster Eye	Kirkpatrick-Baez	Standard Wolter-I	Tilted Wolter-I
Focal distance	2000 mm			
Mass (assuming $\rho = 8.9 \text{ g/cm}^3$)	20 kg			
Size	300 mm×300 mm		Radii=120–341 mm	
Mirror length	40 mm		75 mm	

Table 2. Geometrical parameters to compare the different optical designs.

- The effective area for the Lobster design — at these large sizes — is constant over the entire field of view. At this focal length the effective area for the tilted Wolter-I design is the largest.
- The angular resolution of the tilted Wolter-I design is mostly worse than for Lobster designs, while the best angular resolution is obtained for a Kirkpatrick-Baez design (which also gives the worst effective area). The angular resolution is (ideally, we are not simulating fabrication errors or roughness) perfect on-axis for the normal (non-tilted) Wolter-I design, but it worsens very rapidly off-axis.

Figure 4 shows a comparison of the incident photon distributions in the case of the tilted Wolter-I and the Lobster designs considered above. The distribution of ghost rays (rays reflected on only one optical surface) is different: for the tilted Wolter-I design it is distributed in a flower like shape at some distance from the center, while for Lobsters they are arranged in a cross close to the center of the source position.

5. CONCLUSION

In this paper we summarized the different optical designs that could be used, in a small mission, to accurately localize X-ray sources that are counterparts of gravitational wave events: Lobster eyes, Kirkpatrick-Baez, and a variant of the Wolter-I design based on tilting the shells to increase the field of view.

The evaluated designs can potentially satisfy the scientific objectives required; with the parameters considered in this paper, the tilted Wolter-I design achieves a larger effective area, but the Lobster eye offers a more uniform performance.

A major drawback of the tilted Wolter-I design is the presence of stray light and especially of ghost rays. These are present also for other wide field optical designs, such as Lobster eyes, but the distribution is different: these rays are closer to the source in the Lobster eyes, and also have a regular cross shape, while for the tilted designs they are distributed over a wider area in a much more complex flower-like shape. Future work will investigate methods to mitigate these effects.

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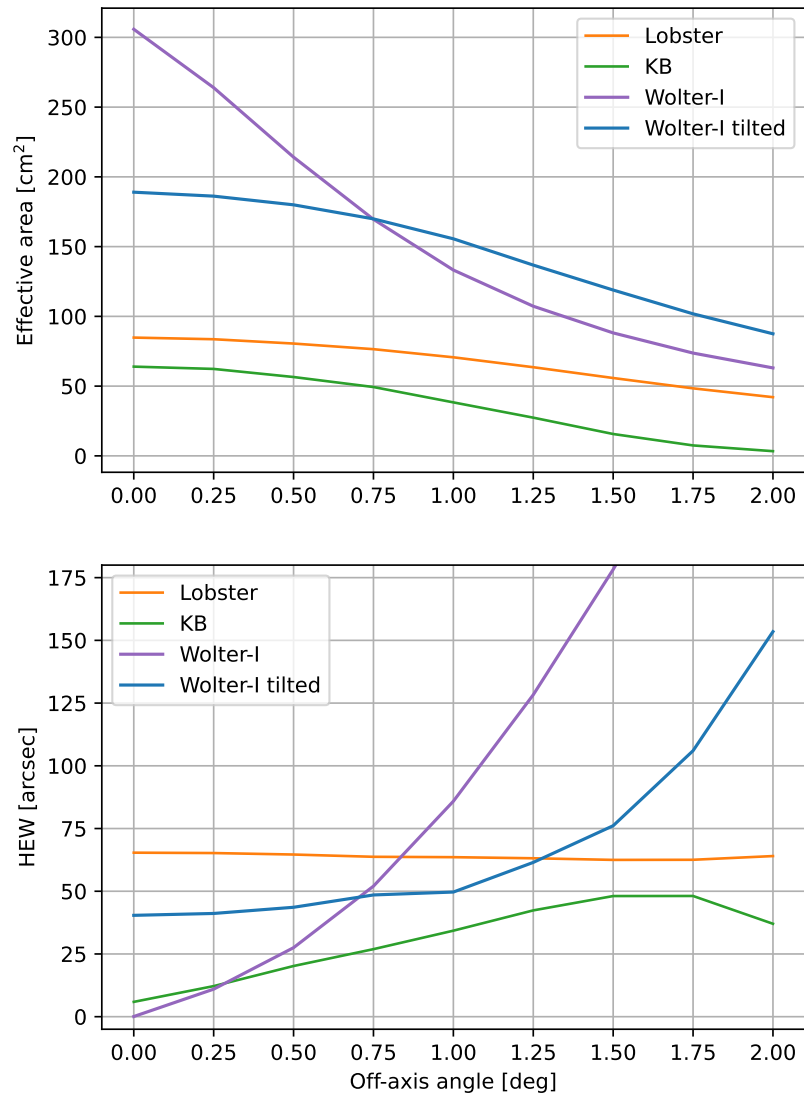


Figure 3. Effective area and half energy width, over the field of view, for the different telescope designs under consideration.

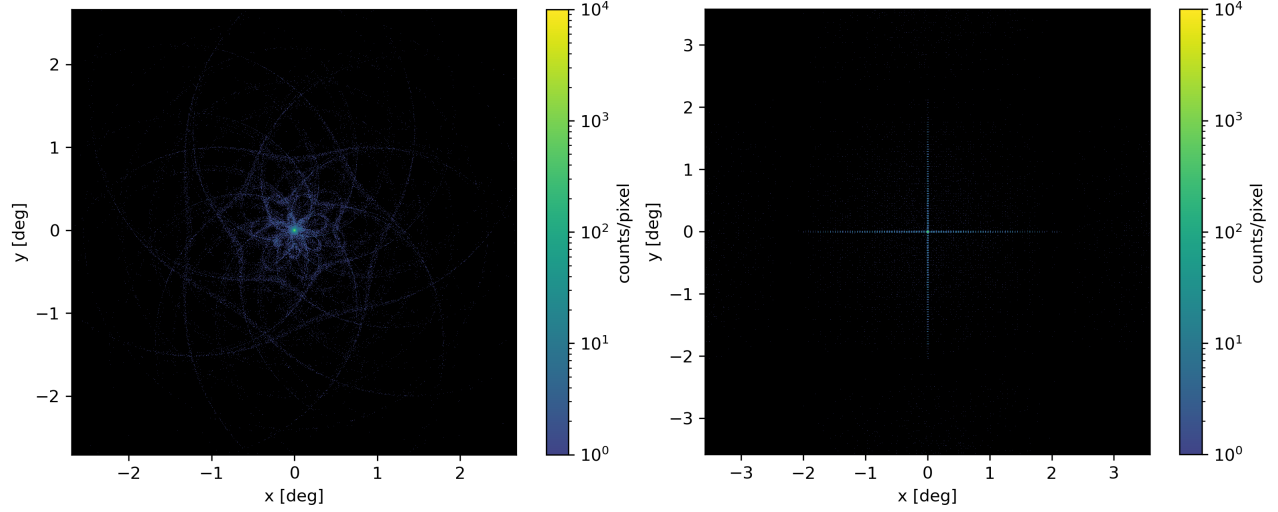


Figure 4. Comparison of the photon distribution in the tilted Wolter-I (left) and the Lobster (right) designs described in the text. The distribution of ghost rays is far from the source in the tilted Wolter-I case, while closer to the source, and in a more regular cross shape, in the Lobster case.

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