

Silicon Pore Optics for NewAthena: optimizing the imaging performance of modular X-ray optics

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ABSTRACT

NewAthena is the next-generation X-ray observatory for astrophysics. It is a flag-ship mission of the European Space Agency that is planned for launch in 2039. One of its distinguishing features is a large effective area of over 1 m² at a photon energy of 1 keV. It allows NewAthena to collect a large number of photons that enable the detection of high-resolution spectra with its micro-calorimeter array X-IFU and detailed images with the Wide-Field Imager instrument. This is made possible by the development of a new focusing optics technology: Silicon Pore Optics (SPO). SPO are produced with components and techniques from the semiconductor industry. This has resulted in modular optics that are light-weight while achieving a high imaging resolution. Compared to other X-ray mirror technologies, the mirrors are thinner than foil optics while improving in optical quality over nickel shells. SPO consist of mirror modules that each contain a small section of 74 nested Wolter-Schwarzschild shells. Over 500 mirror modules are co-aligned to provide a large combined effective area with excellent imaging quality. The modular design of SPO changes the way X-ray optics are produced. A largely automated robotic production facility has been realized, where the components of mirror modules are mass produced. Moreover, the modular design also provides us with opportunities to maximize the optical performance that do not exist for full-shell optics. These opportunities exist at every level, including the individual mirror plates, the combinations of the separate mirror surfaces that provide the primary and the secondary reflections, and the co-alignment of the complete modules. By making smart choices in how the different components are integrated, certain errors can be compensated for. Therefore, even when individual components have small deviations, these need not necessarily result in a degradation of the complete optic. This makes the SPO production process more robust, bringing the optic closer to the nominal design performance.

Keywords: X-ray optics, X-ray astronomy, ATHENA, NewATHENA, Silicon Pore Optics, X-ray telescopes

1. INTRODUCTION

Silicon Pore Optics (SPO) is a new X-ray optics technology developed by cosine and partners for the European Space Agency (ESA) for its upcoming mission “New Advanced Telescope for High-ENergy Astrophysics” (NewAthena) [1,2]. NewAthena is a large-class mission hosting a next-generation X-ray observatory, focused on high-resolution imaging spectroscopy. The science requirements for NewAthena necessitate a large effective area of over 1 m² at photon energies of 1 keV [3]. Combined with the mass constraints of the launch vehicle, this calls for a new optics technology: SPO delivers a high optical performance and large effective area at a relatively low mass.

SPO are modular optics made from silicon wafers by employing techniques from the semiconductor industry [4,5,6]. At the basis are small mirror plates, that are stacked, and stacks are integrated into imaging units called “mirror modules.” Hundreds of modules are co-aligned in the mirror module assembly forming the complete optic. The large number of components requires a mass-production approach, with largely automated production to ensure a high quality is achieved consistently [7].

Any production process results in components with small deviations from the design. Those components that do not meet the requirements are rejected, resulting in a reduced production yield and increased costs. We show that the SPO production process provides opportunities for substantially reducing the effect of these errors.

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In this paper, we summarize the optical design of NewAthena, and for two parameters we demonstrate that an optimized selection of components during the integration steps substantially reduces the impact of errors in the parameters. Compared to other suggested optimization techniques, we argue that these are relatively simple and cost-effective to integrate in a production process. We conclude that this is an advantage of modular optics, and the design of SPO in particular. It allows for optimizing simultaneously the optical performance as well as the production yield and costs.

2. OPTICAL DESIGN OF NEWATHENA WITH SPO

The Wolter-Schwarzschild optical design uses two grazing-incidence reflections to focus an X-ray. This design has often been implemented in full shells, where the sites for primary and secondary reflection are part of the same shell. Mirror shells are nested to increase the collecting area of the optic.

NewAthena employs an approximation of the Wolter-Schwarzschild design using the SPO technology [1,8]. The sites for the two reflections are split over a primary and a secondary mirror that are placed back-to-back. Both have a conical shape. In addition, the shape of the secondary mirror includes a circular curvature in the direction along the optical axis, which we refer to as the meridional curvature. In principle, the relevant quantity is the sum of the meridional curvature of the primary and secondary mirror. For ease of manufacturing, we choose to apply the meridional curvature to the secondary mirror.

The primary and secondary mirrors are implemented as small rectangular plates (figure 1). The plates are stacked, and the stacks integrated into mirror modules. Each mirror module contains two pairs of a primary and secondary stacks. A large number of mirror modules are placed in concentric rings and co-aligned to form the full optic.

The mirror plates are produced from mono-crystalline silicon. A plate consists of a thin light-weight reflective membrane and supporting ribs. When plates are stacked, the ribs form the support structure. They have a wedge shape, which sets the relative angle between consecutive mirrors. Therefore, the relative alignment is built into the plates.

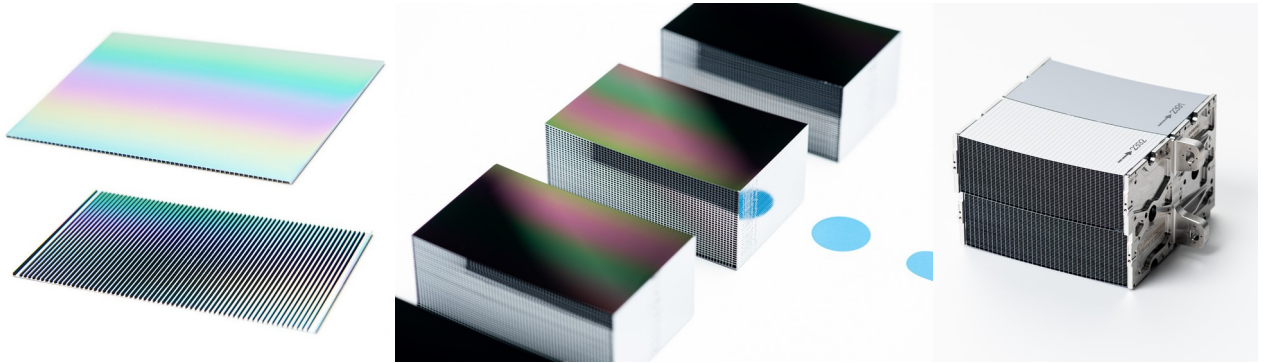


Figure 1. Photos of the components of SPO: a silicon mirror plate seen from the reflecting top and the ribs at the bottom (left), several stacks consisting of 37 reflecting plates (middle), and a mirror module consisting of 4 stacks (right).

3. RESULTS

The production of plates and their integration into stacks are highly automated processes. Each process realizes the design to a certain precision. The errors in the design parameters will follow a certain distribution. At the step of integrating the components, we can optimize their selection to reduce the impact of the errors. Here we present two examples: the wedge angles of plates to be placed in a stack and the meridional curvature of stacks to be integrated in a mirror module.

3.1 Optimize the wedge angle of mirror plates in a stack

The mirror plate production process yields wedge angles with a certain distribution. The deviation from the nominal angle is the wedge error, w_i . We model the distribution of w_i as a Gaussian distribution centered on w_0 with width σ (figure 2). When plates are integrated in a stack, wedge errors are cumulative. As reference, we choose the plate in the middle to be at the nominal orientation. For an odd number of optical plates in a stack, N , the reference plate is at

position $N_{\text{mid}}=(N+1)/2$. Therefore, the orientation of the other plates is determined by the sum of the wedge angles relative to the reference plate, and the deviation from the nominal orientation is the cumulative sum of w_i , W_k :

$$\begin{aligned} W_k &= \sum_{i=N_{\text{mid}}+1}^k w_i \text{ for } k > N_{\text{mid}} \\ W_k &= 0 \text{ for } k = N_{\text{mid}} \\ W_k &= -\sum_{i=k+1}^{N_{\text{mid}}} w_i \text{ for } k < N_{\text{mid}} \end{aligned} \quad (1)$$

For a random draw of N values of w_i from the distribution, the expectation for W_k is:

$$W_k = w_0(k - N_{\text{mid}}) \pm \sigma \sqrt{|k - N_{\text{mid}}|}, \quad (2)$$

which includes a systematic component that is linear in k and a stochastic random-walk part that is proportional to $\sqrt{k}$. The cumulative wedge error is, therefore, more sensitive to the center of the distribution than to its width. As an example, we plot W_k for a distribution with $w_0=\sigma/3$ (figure 3 left). The stochastic part is represented by the 68% and 95% contours around the systematic part. We include a realization of W_k based on values w_i randomly drawn from this distribution, which illustrates the random walk in an individual stack.

The cumulative wedge error can be reduced by optimizing the order of the plates in the stack. Different optimization strategies are possible. We choose to find pairs of plates that largely cancel the stochastic part of the wedge error. In other words, we stack plates in pairs where the sum is close to twice w_0 . This reduces the step size of the random walk. The sorting process has a similar effect on the variance as taking the error in the mean of a distribution, and the standard deviation can be approximated by $\sigma/\sqrt{M}$, with M the size of the pool of plates from which we select. The cumulative wedge error is now:

$$W_k = w_0(k - N_{\text{mid}}) + \sigma \sqrt{\frac{|k - N_{\text{mid}}|}{M}} \quad (3)$$

For example, if simply take the plates of a single stack, $M=N$, the optimization reduces the stochastic component by a factor $\sqrt{N}$ (figure 3 right). If we would optimize the plates of all 4 stacks in a mirror module, $M=4N$, we further reduce the stochastic component by an additional factor $\sqrt{4}=2$.

As another optimization strategy, we could aim for $W_k=0$. In addition to the stochastic component, this would reduce the systematic component as well. To achieve this, we can only use a subset of the distribution of w_i , namely a symmetric part around 0 (figure 2 left). Depending on the value of w_0 , this subset may exclude several tens of percent of the plates based on their wedge error (figure 2 right). This removes the systematic component, and reduces the stochastic component as before (Eq. 3), but note that M now represents the smaller size of the subset of plates from which we select:

$$W_k = \sigma \sqrt{\frac{|k - N_{\text{mid}}|}{M}} \quad (4)$$

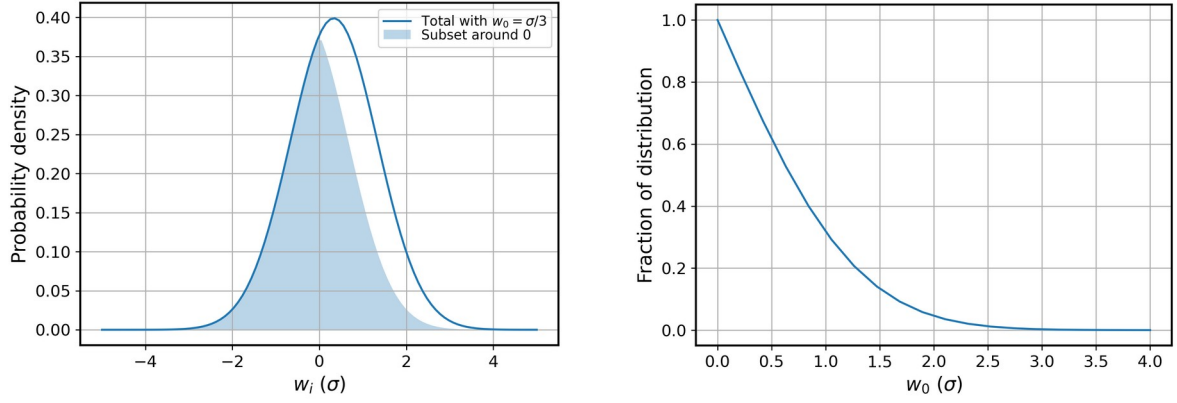


Figure 2. Left: normal distribution of wedge errors of plates, w_i , centered on $w_0 = \sigma/3$. The shaded area is a subset of the distribution that is symmetric and centered on 0. Right: as a function of the center of the distribution, w_0 , the fraction of the distribution that is in the symmetric subset around 0.

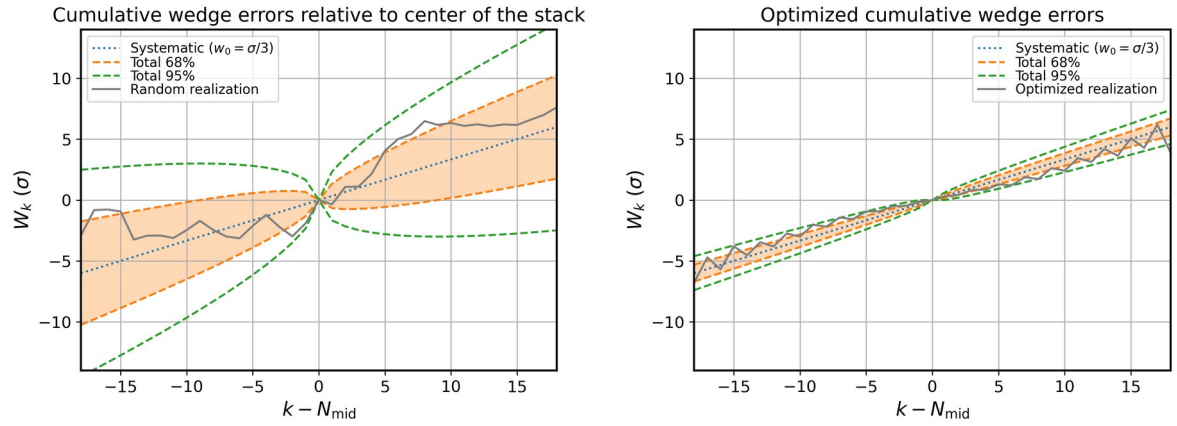


Figure 3. Left: the cumulative wedge error W_k in units of σ as a function of the plate numbering from the reference position in the center of a stack. The 68% and 95% confidence level contour lines of the random walk around the systematic component are shown. The solid line represents a realization of W_k for a random draw of wedge errors from the normal distribution (Fig 2 left). Right: when the optimization of the plate order is included, the systematic component remains the same, but the extent of the random walk around this component is substantially reduced. This is also illustrated by the optimized version of the random realization.

3.2 Optimize the meridional curvature of stacks in a mirror module

The stack production process yields stacks with a distribution of meridional curvature values. We model the error as a normal distribution centered on κ_0 with width σ (figure 4 left). For convenience, we assume that the distributions are the same for primary and secondary stacks. Stacks are integrated into mirror modules in pairs of a primary and a secondary. The meridional curvature error of the primary stack, κ_P , and of the secondary stack, κ_S , are summed to get the total meridional curvature error, $\kappa_{\text{pair}} = \kappa_P + \kappa_S$. When we randomly pair primary and secondary stacks, κ_{pair} follows a normal distribution centered on $2\kappa_0$ with a width of:

$$\sigma_{\text{pair}} = \sigma \sqrt{2} \quad (5)$$

A similar optimization can be implemented as for the wedge error of plates, by finding pairs of primary and secondary stacks that minimize κ_{pair} relative to the center of the distribution. Given N primary stacks and an equal number of secondary stacks, optimization reduces the width of the distribution of κ_{pair} to (figure 4):

$$\sigma_{\text{pair}} = \sigma \sqrt{\frac{2}{N}} \quad (6)$$

For example, if we employ $N=12$ pairs of stacks for the optimization, σ_{pair} is reduced to 28% of the unoptimized value, and for $N=96$ σ_{pair} is reduced to 11% (figure 4 right).

This optimization strategy does not remove the systematic part due to the nonzero center of the distribution, κ_0 . Similar to the optimization of the wedge errors, this can be corrected for by only using a subset of the distribution of $\kappa_{p,s}$ that is symmetric and centered on 0. Depending on the value of κ_0 , this may require excluding a substantial fraction of the produced stacks (figure 4 left).

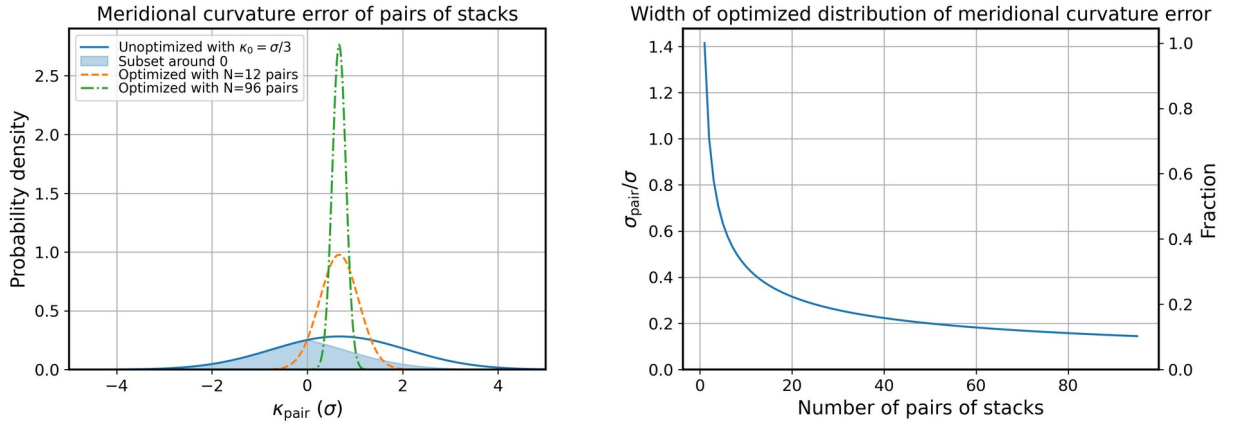


Figure 4. Left: the distribution of meridional curvature error values for pairs of primary and secondary stacks. Optimization of the pairing with a larger number of stacks substantially reduces the width. As unit we use the width of the meridional curvature error distribution for *single* stacks, σ . Furthermore, we place the center of the single stack distribution at $\kappa_0=\sigma/3$, which places the distribution for pairs at twice this value. The shaded region is a subset of the distribution that is symmetric around zero. Right: The width of the distribution of meridional curvature error values of pairs of primary and secondary stacks as a function of the number of pairs used for optimization (Eq. 6). The width is $\sigma\sqrt{2}$ for $N=1$ without any optimization (Eq. 5).

4. DISCUSSION

We have shown two opportunities for compensating errors in the production of SPO. One is the errors in the wedge angle of plates, which can be compensated during the integration of the plates in stacks. The other is the errors in the meridional curvature of stacks, which can be compensated during their integration in mirror modules. Both involve forming pairs of components, where the sum of the quantity has a minimal error. Furthermore, we made a distinction between only reducing the stochastic error and reducing the full error including a systematic part.

Reducing only the stochastic error is relatively simple and does not add substantial costs. We optimize the order in which components are integrated. This requires metrology of all components, such that the relevant quantity is measured. All components are used: there is no yield reduction and associated cost increase. In fact, the yield of the component may actually increase, as larger errors may be tolerated. There is a possible impact on the production scheduling, as we show that errors are reduced more when we base the optimization on a larger pool of components (Eq. 3, 6). Depending on the chosen size of the pool, the integration step is delayed until the required number of components has been produced.

Reducing the systematic error using our optimization method necessarily leads to a yield loss, as a number of components cannot be integrated. This may only be acceptable for a relatively small systematic error. Instead, it may be more cost-effective to optimize the production process of the component to reduce the systematic error.

We have provided statistical estimates of the expected improvements from our optimization method for an individual quantity. In order to see which improvements are needed, their impact on the optical performance must be evaluated. This typically requires a numerical implementation of the optical design and all relevant error contributions. The impact of an error on the point-spread function needs to be evaluated in the presence of all other errors, in order to establish if a reduction of a specific error produces a significant improvement in the over-all optical performance.

Other correction techniques have been proposed in the context of modular X-ray optics, such as correcting the shape and orientation of plates in a stack using so-called flex elements and ultra-fast laser stress figuring [9], or by using thin-film piezoelectric actuators [10]. These techniques are designed for the production of optics with a half-energy width (HEW) better than 1 arcsec. For NewAthena the target is HEW=9 arcsec, and the extra complexity that is introduced in the production chain by these techniques may not be cost-effective, whereas the simple corrections that we propose require minimal changes to the processes.

5. CONCLUSIONS

SPO are a new modular X-ray optics technology where a large number of mirror plates are integrated into stacks, and stacks are integrated into mirror modules. The components are mass-produced in highly automated robotic processes. We have demonstrated how at each integration step the selection of components can be used to compensate errors in the components, thereby bringing the over-all optics closer to the design specification. For the errors that we considered, the stochastic part of the errors can be easily reduced with minimal changes to the production processes. This makes it a cost-effective method for optimizing the optical quality, helping us reach the requirements for NewAthena. Moreover, the presented optimization can be performed for other applications of SPO as well, including Laue lenses, Kirkpatrick-Baez optics, and X-ray interferometers [11,12,13].

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