Characterization of a Hard X-Ray Telescope

As in all physical experiments, instrument calibration has a crucial importance in astronomy. Especially in space astronomy, instruments are aboard orbiting satellites to avoid an atmospheric extinction of radiation from celestial objects. Therefore, instruments must be calibrated accurately and precisely before launch. This is because, obviously, there is very little chance to calibrate and tune instruments after they are launched into space. This research aims to develop a calibration technology for a newly developed astronomical instrument, hard X-ray focusing mirrors, which is only possible at a large synchrotron facility, SPring-8. The major part of this article is described in detail by Ogasaka *et al.* [1].

The recent progress in X-ray optics technology has realized the "hard X-ray focusing telescope," which utilizes reflective optics to focus X-rays above 10 keV. At such high energy, an effective optics is difficult to construct with ordinary total external reflection mirrors. Instead, multilayer mirrors are used, which utilize Bragg's reflection by the artificially layered structure of heavy (reflecting) and light (spacer) materials. Figure 1 shows a picture of the hard X-ray mirror developed for the balloon-borne observation experiment called SUMIT. The SUMIT hard X-ray mirror consists of 199 pairs of ultra-thin (0.2 mm thickness) Wolter-I optics, whose surfaces are coated with depth-graded Pt/C multilayers. Its energy bandpath reaches 80 keV, about an order-of-magnitude improvement compared with previous mirrors.

The multilayer hard X-ray mirror is considered a promising technology for future X-ray astronomical research. To fully utilize its new performances, however, the mirror must be calibrated before launch, primarily, to characterize its performance and, secondarily, to construct response matrices that are crucially important for data analysis. To perform a comprehensive characterization of hard X-ray mirrors, an experiment setup has been established at **BL20B2**, one of the medium-length beamlines at SPring-8. The advantages of the experiment at BL20B2 are high intensity of the X-ray beam and large distance to the X-ray source. As the separation between the X-ray source and sample to be measured increases, the beam divergence decreases, but the beam intensity decreases as well. At a synchrotron facility such as SPring-8, however, the source intensity is high enough to compensate it.

Fig. 1. Hard X-ray mirror on board SUMIT balloon experiment. 199 pairs of conically approximated Wolter-I optics are nested coaxially. Aperture diameter, mirror length, and focal length are 40 cm, 26 cm, and 8 m, respectively.

The experiment first took place in 2003, when the hard X-ray mirror for the US-Japan collaborative balloon experiment InFOCuS was tested. Since then, the experiment setup and measurement technologies have been upgraded through calibration of InFOCuS and the Japan-Brazil collaboration balloon experiment SUMIT. Initial results of these experiments are summarized in Ref. [1].

At BL20B2, we are now able to measure key parameters such as effective area, which is crucial to derive the X-ray flux of the observed object, and a point spread function (PSF), which is an intrinsic image blur of the optics and is relevant to analyze the spatial structure of the objects. Figure 2 shows a picture of the InFOCuS X-ray mirror placed at hutch 2 of BL20B2 and an example of a focused image (PSF) measured. In addition, the focusing characteristics of individual reflectors are also evaluated by restricting the area of X-ray illumination. Such measurements are considered as a "diagnostics" to understand the source of the image blur and decrease in effective area, and are only possible using a bright synchrotron light source.

One of the outputs from the experiment is the establishment of an "X-ray optical tuning" method. By this method, we can reduce the image blur by iteratively tuning the optics by looking at the focused image. When the X-ray mirror is assembled, there still are errors in the mechanical positions of reflectors owing to the limited accuracy of machining and assembling. Such uncertainties, on the order of a few to a few tens of μm, cause image blur, so they need to be corrected. They are measureable by analyzing an error in the focused image. We have established a method to derive mechanical error from the focused image and to correct it. Details of the optical tuning are described by Ogasaka *et al.* [2] and references therein.

Figure 3 explains how the optical tuning is performed. In this case, positional errors of radial support bars are corrected. Such errors cause off-roundness in the focused image and change in the

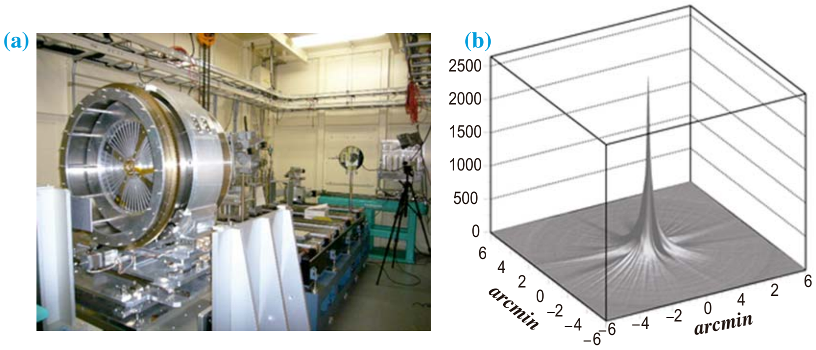

Fig. 2. **(a)** Photograph of InFOCuS hard X-ray mirror mounted on the 5-axis sample positioning stage placed at hutch 2 of BL20B2. **(b)** Example of a measured focused image of InFOCuS mirror. Data was taken at 30 keV. The half power diameter of the image is about 2 arcmin.

focal length. We derive the amount of adjustment to correct them through the image analysis, and then apply the adjustment. Figure 4 shows focused images of the SUMIT hard X-ray mirror measured at 30 keV, before and after the optical tuning. It took us several iterations before obtaining the final result. The image quality was improved from 2.4 to 2.0 arcmin (HPD: half power diameter). In terms of off-roundness, the error was reduced from 1.4 to 0.3 arcmin (HPD equivalent), which means that the off-roundness was almost completely eliminated. A more qualitative discussion is found in Ref. [2]. The optical tuning requires a rapid measurement of the focused image. In our case, it takes only about 4 h for one iteration (measurement and tuning), while it has been almost a day or even more without bright synchrotron light.

Japan's X-ray astronomy community is currently developing the next generation X-ray observatory ASTRO-H. It is a national mission initiated by JAXA and is scheduled for launch in FY2013 [3]. ASTRO-H will have two multilayer hard X-ray telescope systems to carry out new astrophysical research such as exploration of hidden black holes at the core of galaxies or study of the particle acceleration mechanism in the universe. The ground calibration of ASTRO-H hard X-ray mirrors will take place at BL20B2.

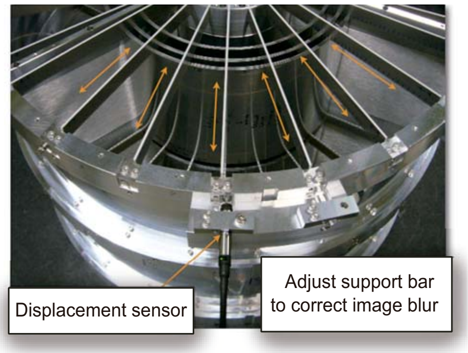

Fig. 3. Hard X-ray mirror under optical tuning. In this case, the positions of radial support bars are tuned. A displacement sensor is attached at the outer end of the radial bar to measure the adjusted amount.

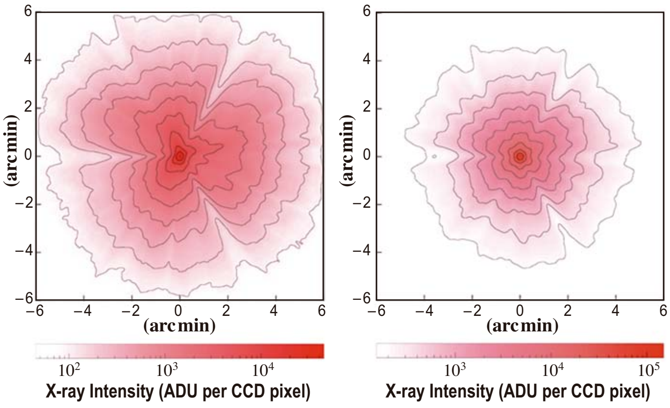

Fig. 4. Focused image of a hard X-ray mirror measured at 30 keV. The gray scale shows focused intensity on a logarithmic scale between 0.25 and 100% peak intensity. The contour interval is logarithmically constant over the same range. The left panel shows the image taken before the tuning, whereas the right panel shows that taken after the tuning. The off-roundness error was reduced from 1.4 to 0.3 arcmin, and the image HPD was from 2.4 to 2.0 arcmin.

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