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The problem of the calibration of SIMBOL-X X-ray telescope

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Abstract. One of the main problems concerning the implementation of the telescope with a long focal length is related to the calibration tests. Soft X-ray (0.1 - 10 keV) telescopes with good imaging performances like e.g. XMM, have been so far calibrated by full illumination with X-rays. However, in the case of Simbol-X, a number of different issues have to be solved, as e.g. the area loss due to the finite source distance in presence of a long focal length and the different X-ray reflectivity response from the parabolic section of the multilayer-coated mirrors with respect to the hyperbola. In this paper we will propose a possible configuration to be adopted that would satisfy the mission requirements.

Key words. X-rays: Wolter-I, calibration, pencil beam

1. Introduction

In Europe it is available in Munich the 130 m long PANTER Test facility operated by MPE, that is used to calibrate several X-ray telescopes (like Rosat, XMM, SAX, Swift). The utilization of the PANTER facility with 20 m focal lengths poses challenging practical problems, due to the difficulties of positioning and handling the optic inside the vacuum tube (as the focal length would not fit into the 12.5 m-long handling chamber normally used for mounting the optics). Considering that the diameter of the Simbol-X telescope is not much less than the internal diameter of the long (123m) vacuum tube and that the pencil beam setup need a complex tip-tilt jig supporting the telescope, it could be necessary to modify the facility. Apart this practical problem, there are other difficulties to consider that are presented in the following sections.

2. Problems with long focal length

The main problem is the reduction of the Effective Area (EA) (Fig. 1). With a long focal length like that of SIMBOL-X (~20m) and with a finite distance of the X-ray source, the X-rays reflected near the parabola front-end miss the reflection on the hyperbola and therefore the EA in full-illumination setup for double reflection as measured e.g. at PANTER would be negligible. The fractional loss of EA Q is

$$Q = 1 - (\alpha - \delta)/(\alpha + \delta) \qquad (1)$$

α is the nominal angle of the parabola, δ is the divergence angle. $\alpha + \delta$ is the incidence angle on the parabola and $\alpha - \delta$ is the incidence angle on the hyperbola. Due to the dependence of the reflectivity on the incidence angle, the reflectivity diagram $R(E)$ is different for the parabola and for the hyperbola and the single-reflection efficiency cannot be directly measured from effective area information, but a proper modelization of the multilayer stack has to be performed.

It has also to be specified that the distance of the detector from the optic (f') is not equal to the nominal focal length (f), as it increases with the distance of the source, D:

$$1/f = 1/f' + 1/D \tag{2}$$

At the PANTER facility $D \simeq 110$ m, hence if f = 20 m $\Rightarrow f = 24.44$ m.

3. Setup to reduce the divergence of the beam

A possible way to get around the finite distance of the X-ray source is the pencil-beam setup. This method is often used to characterize selected mirror sectors along with a thin X-ray beam emerging from a slit drilled in an opaque screen. In these conditions, the beam divergence is strongly reduced and the optic angular offset can be properly set, in order to rule out finite distance effects for the considered mirror sector. The main drawback of this method is the strong reduction of the mirror effective area and, consequently, the time requested to return an affordable photon count. This can be, indeed, reduced by increasing the incident X-ray photon flux.

Successful pencil-beam EA characterization were performed at PANTER with multilayer-coated optics prototypes with a single mirror shell.

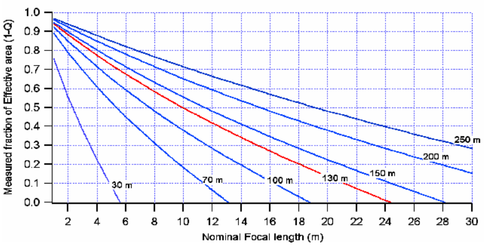

Fig. 1. Measured fraction of effective area, for different possible distance source-detector.

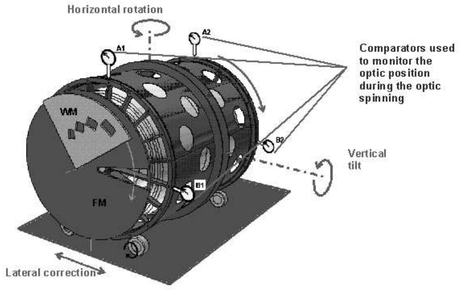

Fig. 2. Scheme of the manipulator.

For many shells (e.g. 100 for SIMBOL-X), in order to conveniently reduce the needed time for the characterization, each window can be used to illuminate a small group of shells that will be characterized together, provided that the windows are narrow enough to limit the beam divergence ($\ll \alpha$) in order to avoid the finite distance effects. A possible implementation of the manipulator (Fig. 2), that is the system on which the case with the optics is positioned for calibrations, for optics with several mirror shells, is here discussed. A system of slits is devoted to the limitation of the X-ray beam divergence when impinging on the mirror shells: two masks, a fixed one (FM) and a rotating one, the windows mask (WM), allow the selection of different group of shells creating a window with an angular sector shape intersecting the windows of the two masks. The width along the radial direction is W and the height, along the circumference, is H. The optical module is laid on 4 wheels, by means of which the module can be spun about its symmetry axis, and all the mirror surface is tested while keeping the better incident angle. Although the divergence is reduced, the distance of the source is finite, so the position of the detector is set by eq (2).

During the axial spin, four comparators are used to record the optic position. The optic alignment can be corrected, if needed, by mechanical adjustments or by an image reconstruction via software. In this case the shells must be integrated in the case with a sufficient precision of alignment between the optical axis and the mechanical axis; if this is not possible, that difference has to be measured accurately

Table 1. Examples of window masks to be adopted for the pencil-beam setup.

Case	EA %	N of windows	R [mm]	*W* [mm]	*H* [mm]
			323.5	12.7	83.7
1	95	23	219.9	8.7	57.4
			128.7	5.2	34.1
			323.5	26.2	167.5
2	90	11	219.9	18.6	119.0
			128.7	11.1	71.3

to allow the off-line focal spot reconstruction. Even though the rotation along an axis passing through the parabola/hyperbola intersection plane does not cause any shift of the image in the focal plane, but only changes in the effective area, lateral shifts of the image result in a lateral displacement of the optic.

To constrain the window size the effect of X-ray divergence within the window has to be computed. For the width (W) it is simply computed using Eq. 2 replacing δ with $\delta_{\text{shell-est}} - \delta_{\text{shell-int}}$. The symbol $\delta_{\text{shell-est}}$ is the divergence for the outer shell inside the window and $\delta_{\text{shell-int}}$ is the divergence for the inner shell inside the window. For the height (H) δ in Eq. 2 is replaced by $\delta(1 - \cos\theta)$ where θ is the half angular aperture of the window.

We will consider two different sets of mask to forecast the time needed to sample all the collecting surface of the optics (Tab. 1). In Tab. 1 θ is limited to 7.5° for case n.1 and to 15° for cases n.2 in order to maintain all the windows in one disk (WM in Fig. 2).

A continuous spinning of the optic would allow the minimization of the number of measurement: in this case the number of exposures simply equals the number of adopted windows.

4. Estimation of the integration time for EA and HEW

A preliminary evaluation of the integration time is presented hereafter considering to measure 3 consecutive measurements in separate photon energy range at PANTER facility.

For the effective area measurement of the whole mirror module the exposure has to be repeated N times (number of windows in Tab. 1), so the total characterization time is approximately $\Delta t = 3(N\Delta t_R + \Delta t_d)$ where Δt_d is the time needed for the direct beam and Δt_R for the focused one.

The X-ray source brilliance cannot be set arbitrarily high. In fact, the pileup avoidance prescription sets as a maximum recorded photon flux during the exposure one photon per frame per group of adjacent pixels, over all the continuum X-ray energy band.

It can be demonstrated that, within the pileup avoidance constraint, the minimum squared EA error $\langle\epsilon_A^2\rangle$ for a single window exposure for a sub-critical source brilliance (B< B_{max}) can be written as

$$\langle\epsilon_A^2\rangle = \frac{D^2}{(1-\chi)A_R\langle B\rangle\Delta E}\left(\frac{8}{F\Delta t_R} + \frac{1}{\Delta t_d}\right) \quad (3)$$

with the assumption that $\langle R^2(E)\rangle \sim 1/4$. The symbols are:

χ: the fraction of OOT (out-of time)
F: filling factor
A_R: the entrance window area in use
ΔE: considered energy interval
$R(E)$: average reflectivity of the shells

Regarding the HEW the formula of the error is a modification of Eq. 3:

$$\langle\epsilon_{HEW}^2\rangle = \frac{8\pi D^2}{(1-\chi)A_R\langle B\rangle\Delta E\Delta t_R} \quad (4)$$

For instance, to obtain HEW measurements at three different energies with an error of 5%, an integration time of 8 to 28 hours is required, depending on the number of used windows and the intensity of the source. The former time would be needed with 11 windows and $\langle B\rangle/\langle B_{max}\rangle$=75%, while the latter corresponds to 23 windows and $\langle B\rangle/\langle B_{max}\rangle$=50%. With the same fluxes, number of windows, and error limits, the integration time for EA would be 15 to 48 hours with a in-focus measurement, or less, if the calibration is performed out of focus.

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