A determination of the HRMA optical axis position using a raster scan of the star HR1099

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At high energies, the HRMA effective area decreases with the off-axis angle, θ, quite rapidly. For example, at $E = 8.6$ keV and $\theta = 8 - 10'$ (the ACIS-I edge), a $1'$ error in θ translates to a 10% error in the effective area (less at lower energies). Assuming that the goal is 1% area accuracy at all energies, the optical axis position (its y and z coordinates) should be known to within $0.1'$. Prior to calibration, it may be uncertain by up to $2'$ (static error). The optical axis position also bears on the focus calibration — the focus x coordinate differs by $\sim$200 μm between the off-axis angles of 0 and $2'$.

The most direct way to determine the optical axis position is to find at what coordinate the effective area reaches its maximum. However, this would require very good statistics at high energies (where the effective area depends on coordinate sufficiently strongly), a nonvariable source and accurately known detector uniformity, so this direct approach appears to be impractical. A more economical way seems to be to find the optical axis position minimizing the PSF width, since the PSF width depends on the off-axis angle much stronger than does the effective area (see the figure below). Simulations (detailed below) show that the required position accuracy may be achieved with about 40 short offset exposures of a point source, covering the central $\theta = 4 - 5'$ of the field, each exposure producing 1000–3000 photons in the wide band. The PSF ellipticity also is a sensitive indicator of the optical axis position (the ellipticity changes from near 0 on-axis to 0.5 at $2'$ off-axis), but it requires more photons per image to achieve a similar accuracy.

The optical axis position needs to be determined for only one detector. If this is not obvious, consider the following: if we determine, using any one detector, at what coordinate in the sky the mirror optical axis is directed, then hold the mirror and shift the SIM, we would know the position of the optical axis in any other detector if the sky-to-detector coordinate transform is known. The HRC seems to be the best choice for this measurement, since it has pixels small enough for on-axis PSF study and can handle a brighter source, while energy resolution is not necessary.

Simulations

SAOSAC rays (current as of 4 March 1998) at 1.5 kev and 6.4 kev were projected onto HRC-I using MARX, assuming an additional blur of $0.34''$ rms diameter due to the aspect reconstruction. I considered pointings at $\theta = 0 - 5'$ with $1'$ step, at 8 position angles (ϕ) 45° apart. For the inner $\pm 2'$, a $0.5'$ step was also considered. The HRC-I plane was put at the focal distance as well as 200 μm closer to the mirror, the latter corresponding to the worst-case scenario of the focus erroneously determined at $2'$ off axis. For each simulated point source image (consisting of 100–10000 photons), the source position was determined by averaging the photon coordinates within $r = 8'' = 60$ HRC pixels (this r is chosen arbitrarily big). A radial profile was accumulated, from which the radii encircling 50% and 90% of the total flux (within $r = 8''$) were determined. These data (either the 50% or the 90% radii) as a function of the detector coordinate were fit by a 2-dimensional symmetric parabolic function, whose minimum was assumed to be at the optical axis position. Statistical accuracy of this position was determined by Monte-Carlo simulations using 10 or more random realizations. The results are given in the table below. The real optical axis is at (y,z)=(0,0). The values of $(y_{\rm mean}, z_{\rm mean})$ and (σ_y, σ_z) correspond to its average fitted position and scatter in arcminutes, for different numbers of photons per image.

Photons per image	$y_{\rm mean}$	$z_{\rm mean}$	σ_y	σ_z
1. $E = 1.5$ keV, detector in focus. Fit the 50% radii:				
(a) Use $\theta = 0, 1, 2, 3, 4, 5'$; $\phi = 0, 45, 90, 135, 180, 225, 270, 315°$:				
1000	–0.024	–0.082	0.027	0.025
300	–0.019	–0.079	0.052	0.049
(b) Use $\theta = 0, 1, 2, 3, 4'$; same ϕ:				
1000	–0.023	–0.082	0.024	0.031
300	–0.023	–0.081	0.042	0.050
(c) Use $\theta = 0, 1, 2, 3'$; same ϕ:				
1000	–0.035	–0.081	0.027	0.031
300	–0.035	–0.080	0.054	0.059
(d) Use $\theta = 0, 1, 2'$; same ϕ:				
1000	–0.067	–0.094	0.031	0.047
300	–0.074	–0.093	0.075	0.075
100	–0.074	–0.080	0.144	0.131
(e) $\theta = 0, 1, 2'$; same ϕ (slightly newer SAOSAC simulations):				
10000	–0.084	–0.116	0.014	0.013
(f) Use $\theta = 0, 0.5, 1, 1.5, 2'$; same ϕ (newer simulations):				
10000	–0.089	–0.121	0.012	0.014
2. $E = 1.5$ keV, detector in focus. Fit the 90% radii:				
(a) Use $\theta = 0, 1, 2, 3, 4, 5'$; same ϕ:				
1000	–0.028	–0.093	0.028	0.021
(b) Use $\theta = 0, 1, 2, 3, 4'$; same ϕ:				
1000	–0.011	–0.091	0.035	0.029
300	–0.006	–0.091	0.058	0.051
3. $E = 6.4$ keV, detector in focus. Fit the 50% radii:				
(a) Use $\theta = 0, 1, 2, 3, 4'$; same ϕ:				
1000	–0.048	–0.061	0.024	0.033
4. $E = 1.5$ keV, detector off focus by 200μm. Fit the 50% radii:				
(a) Use $\theta = 0, 1, 2, 3, 4'$; same ϕ:				
1000	–0.023	–0.109	0.025	0.031
300	–0.022	–0.104	0.046	0.060

The following is notable:

• There is a significant, about $0.1'$, displacement of the point of the narrowest PSF from the true optical axis along the z direction. This systematic offset is not big compared to the accuracy requirement, and besides, it can be taken into account once the raytracing is validated by the in-flight observations.

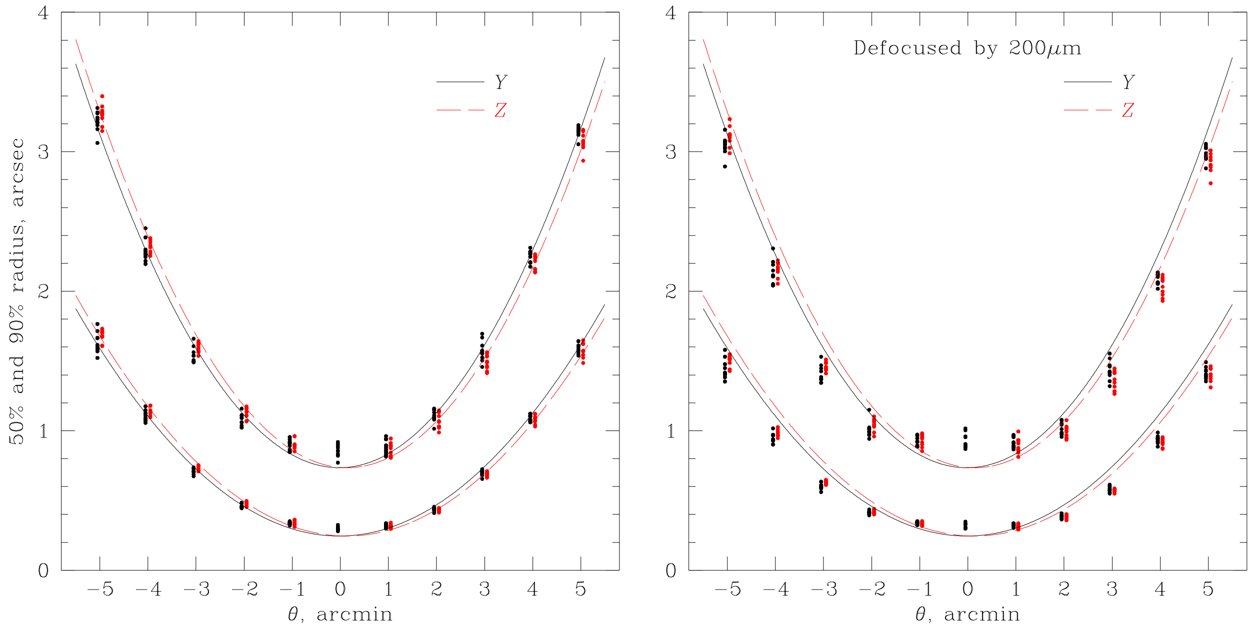
• The position accuracy improves exactly as $\sqrt{N}$ where N is the number of photons per image, when other parameters are equal (compare items 1d-1e in the table).

• Defocusing by as much as 200μm does not strongly affect the measurement (compare items 1b and 4a; see also the figure). It does affect the PSF ellipticity, which is not analyzed here but will provide supplementary data, using the proposed calibration setup.

• Assuming the raytracing is adequate, there is no significant energy dependence of the measured axis position (compare items 1b and 3).

• Expanding the off-axis angle coverage from $0-2'$ to $0-3'$ to $0-4'$ improves the accuracy and possibly reduces the systematic offset mentioned above, but using still greater θ does not add to the accuracy (items 1a-1d). Using a smaller step in θ does not improve it either (compare items 1e and 1f).

• Use of the 50% and 90% radii results in similar accuracy and similar systematic offsets of the fitted optical axis position (items 1 and 2). Of course, they do not constitute completely independent datasets.



The figure above shows the 50% and 90% radii along the y and z directions (the sign is arbitrary). Data along the diagonal directions were also used in the fit but are not shown for clarity. Each image has 1000 photons, and at each θ there are 10 simulated data points in the figure (the z data points are slightly shifted to the right for clarity).

Left panel shows the in-focus data together with the respective cross-sections of the best-fitting parabolic surfaces corresponding to items 1a and 2a in the table. At $\theta = 5'$, the PSF width is already 4–6 times wider than on axis and this effect is readily measurable; there is no need to use greater offsets. Compare this to the effective area drop by only 20% at $10'$ off axis at the energies of 1–2 keV. This illustrates why the proposed calibration method is economical.

Right panel shows what happens if the focus is determined incorrectly by 200μm (here the detector is shifted closer to the HRMA). Models are the same as in left panel for ease of comparison. Defocusing by this amount does not significantly affect the accuracy of the optical axis determination, although the model parabolic function becomes a poor description of the PSF angular dependence.

Proposed observation setup

A suitable calibration source for this measurement seems to be the star HR1099, giving about 6 cts/s with HRC-I. Exposures shorter than 500 s would probably be impractical, since each maneuver will take from 30 to 300 s in the nudge mode. A 500 s exposure will produce about 3000 photons. With such a photon number the statistical accuracy of the described measurement will be more than sufficient ($\ll 0.1'$) and safe against any sudden decrease of the flux of this star. Note, however, that if this flaring star *increases* its flux by a factor of a few, the flux in the PSF core may exceed the HRC linearity limit, so a fainter source may be a safer choice.

By the time of this measurement, the rough position of the optical axis should be known to perhaps $0.5' - 1'$, e.g., from multiple position focus measurements. To allow for a possible $1'$ offset of the optical axis from its presumed position, I would propose to cover off-axis angles from 0 to $5'$ with the $1'$ step as shown below:

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These 37 pointings each of 500 s duration add up to a total of 19 ks, not including the maneuver overhead. There is some possibility to reduce this total exposure, unless a fainter source is selected instead of HR1099.