Mirror profile diagnostics from intra-focal X-ray imaging

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ABSTRACT

One of the problems often encountered in X-ray optics is the assessment of the optical quality of mirrors that are not accessible to profile metrology. The direct proof of the optical performances can be obtained from an in-focus X-ray measurement, but this often requires a facility that is several meters long, and in addition does not provide a feedback to a actuator system, if present, because all the information regarding the mirror profile is collapsed into the the focal spot. However, this information can be retrieved from an intra-focus measurement, as usually done in Hartmann tests. We present an alternative method to diagnose the X-ray mirror profile, using an intra-focal, near-field image of the focused beam, without using an Hartmann plate. This method is well known to optical astronomers since the 80's in astronomy, but has not been applied to X-rays – at least to our knowledge. In addition to the prediction of the optical quality of a focusing mirror, the reconstructed profile can be used to drive the actuator array of an X-ray active mirror under X-ray full illumination.

1. TESTING MODULAR STACKS OF MIRRORS FOR LARGE X-RAY OPTICS

- The optics of future X-ray imaging telescopes will need to conjugate high angular resolutions and high effective areas, with a low mass/effective area ratio in order to ensure the telescope operation in space. The optical module will comprise thin, densely stacked, precisely figured mirrors made of a lightweight material like, e.g., Silicon or glass. The shallow incidence angles (< 1 deg) and the large mirror apertures (> 1 m) at play entail focal lengths of tenths of meters and make impossible to manufacture monolithic mirrors to be nested in modules. Rather, a modular approach has to be adopted, assembling stacks of smaller, tightly stacked foil segments after endowing them with a focusing profile like the Wolter's. In particular, the hot-slumping approach has been developed in the last years at INAF/OAB, financed by ESA, aiming at demonstrating the feasibility of high angular resolutions (< 15 arcsec) with mirrors made of thin slumped glass foils (**ref. 1**). The final demonstrator is shown in **Fig. 1.**
- A fundamental step is the assessment of the X-ray optical quality of the modular elements produced, in terms of Point Spread Function (PSF) or Half-Energy-Width (HEW, i.e., twice the median value of the PSF). Even though this can be effectively simulated from the analysis of the surface profile and roughness measurements, a direct proof of the attained angular resolution comes from a direct, in-focus measurement in X-rays.
- However, the focal length cannot always be matched because the X-ray facility is not long enough. In this poster we are presenting a method that can be used to derive the mirror shape from an intra-focal exposure. The concept is similar to the "Roddier test" (**ref. 3**) used in optical astronomy since the 80's as wavefront sensor, but applied to X-rays (**ref. 4**).

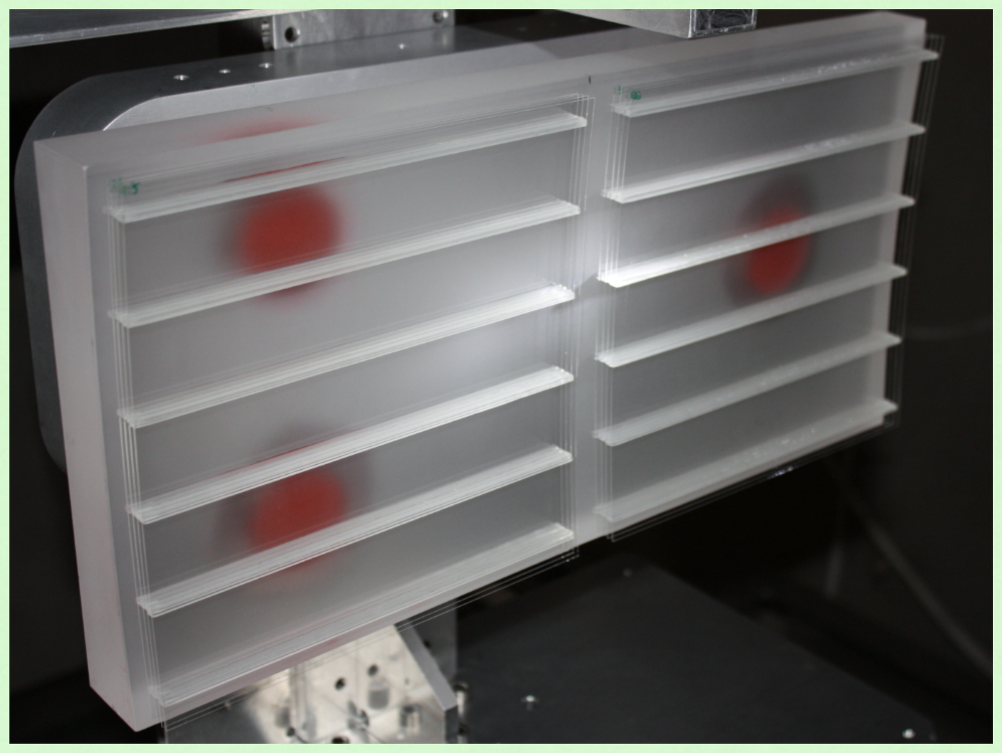


Fig.1. the Proof of Concept No.2 (PoC#2), an example of Wolter-I double stack with 4 layers of glass foils figured via the hot slumping technique and integrated via stiffening ribs (Ref. 1).

2. INTRA-FOCAL MEASUREMENT AT THE PANTER X-RAY FACILITY

✓ The in-focus measurement in X-rays can be done in a large X-ray facility like PANTER (MPE Neuried, Germany, **ref. 2**), which in addition was extended in 2012 to be able to match focal lengths up to 20 m, the one foreseen for the IXO telescope. However, the utilization of the extension could not be scheduled in spring 2013 to perform the in-focus tests of the demonstrator. For this reason, the test had to be dealt in intra-focal setup (8 m distance from mirror).

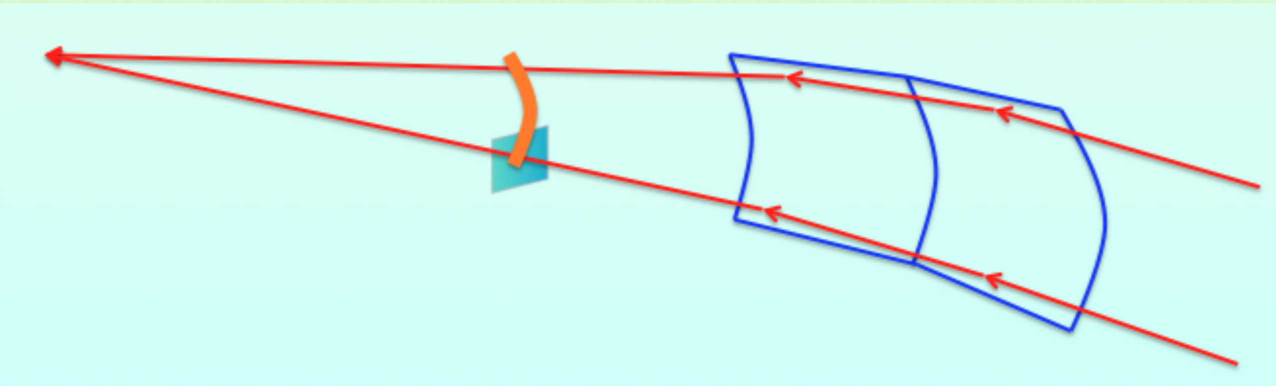


Fig. 2: the concept of intra-focus measurement. The intrafocal trace (133 mm high) should ideally look like an arc of uniform thickness and brightness. Figure errors change the intensity map of the trace.

✓ The intra-focal image of a ideal mirror should look like an uniform arc of predictable size (**fig.2**). However, the mirror imperfections cause a modulation of the intensity recorded intra-focus. In this measurement, the trace was scanned using the TRoPIC detector (19.2 mm size, 75 µm pixel size) in use at PANTER at the X-ray energy of 0.27 keV.

✓ The measurement has been performed in single reflection setup on the parabola and the hyperbola separately. This is obtained by doubling (**fig. 4**) or nulling (**fig. 5**), respectively, the incidence angle on the primary segment.

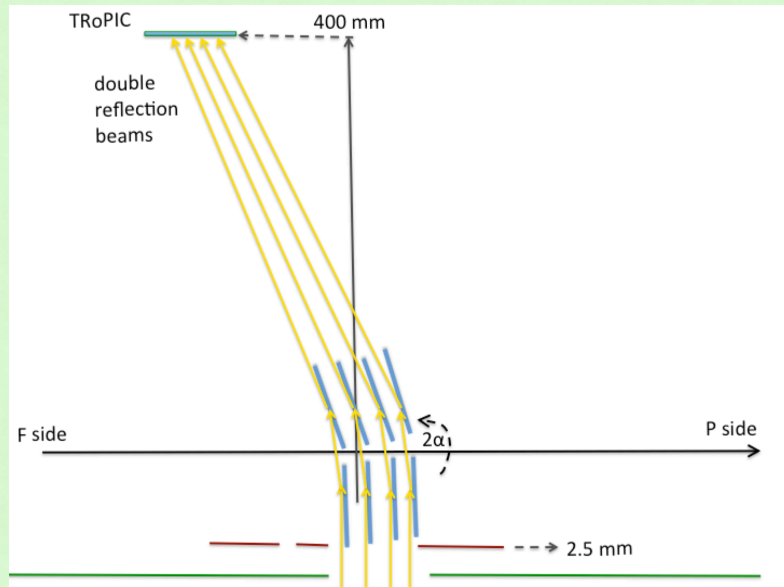


Fig. 3: mirror alignment in double reflection (viewed from top).

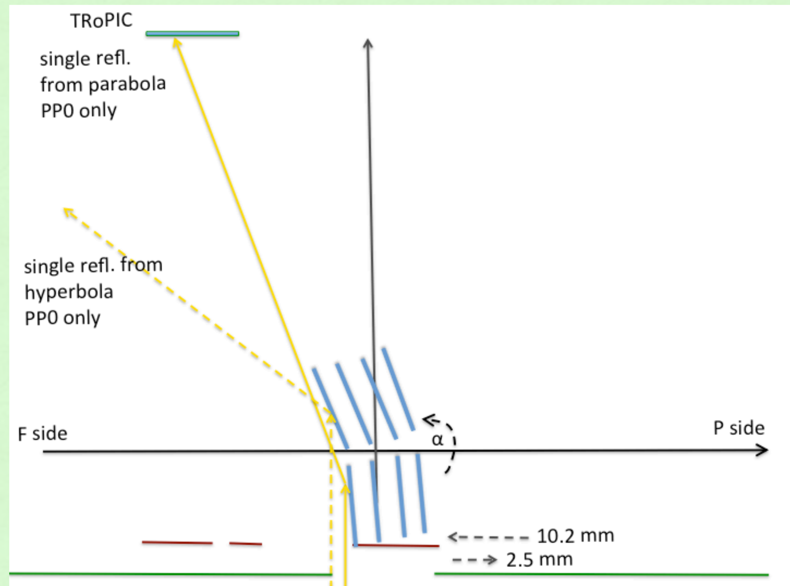


Fig. 4: mirror alignment for parabola single reflection.

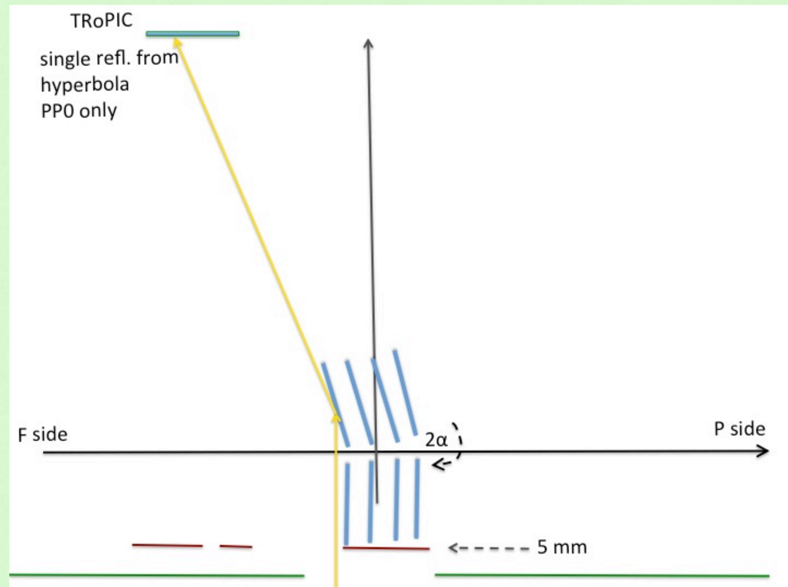


Fig. 5: mirror alignment for hyperbola single reflection.

✓ The results of the TRoPIC scans are shown in **Fig. 6**. They exhibits a width modulated by the periodicity of the rib underneath the glass. The ribs locations are marked by a trace width close to 4.5 mm (the nominal one) and a quasi-uniform intensity distribution: this means that the glass profile at the rib locations is very close to the nominal profile, i.e., the shape of the accurately figured integration moulds has been replicated under the ribs.

✓ The trace becomes gradually broader in the infra-rib space, where the glass spring-back prevails. The surface topography is affected by small mid-frequencies that modulate the brightness map in quasi-parallel lines, which are suppressed at locations corresponding to the ribs positions. Both traces are sharp but at the two ends, where the intensity lines are clearly scattered around by a locally higher roughness.

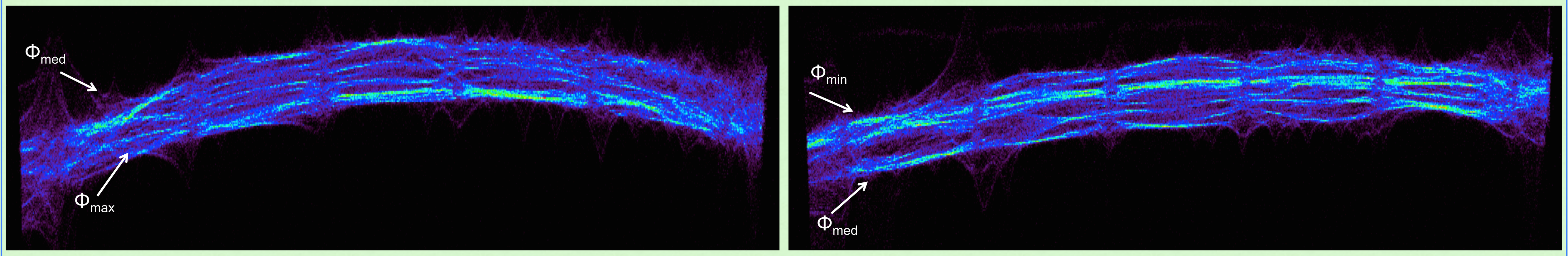


Fig. 6: single reflection traces of the (*left*) parabolic and (*right*) hyperbolic mirror, obtained by scanning the TRoPIC detector in the length direction. The true image fields are 13.3 cm x 2 cm.

3. MIRROR PROFILE RECONSTRUCTION AND EXPECTED OPTICAL QUALITY

The basic principle we adopt to reconstruct a mirror profile is shown in **Fig. 7**: *convex surfaces concentrate the light, concave surfaces spread it out*. Hence, the mirror profile curvature varies along the optical axis (the x coordinate, toward the focus), yielding a local variation of the intensity along the direction locally orthogonal to the trace and oriented toward the PoC#2 optical axis (the z_D coordinate) on the detector plane at a distance D from the mirror. We preliminarily assume that:

1. geometrical optics can be applied, i.e., interferential effects like X-ray scattering are negligible;
2. the deflection out of plane caused by roundness errors is negligible;
3. *D* is small enough to avoid the rays to cross each other, but at the same time large enough to allow the reflected rays to converge or diverge;
4. *D* is much larger than the mirror length.

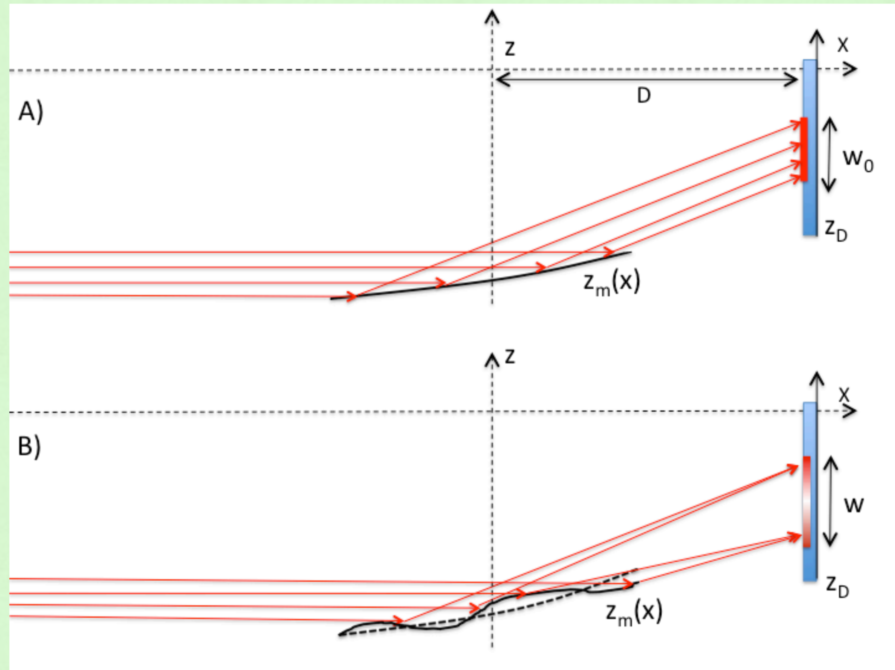
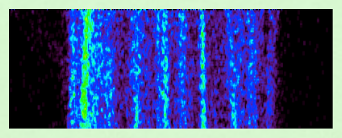


Fig. 7: A) a perfect mirror would return a uniform trace; B) the presence of defects affects both width and brightness variations of the trace.

The image is sliced at the lateral resolution desired and the intensity profile is obtained by projection over the z_D axis. The resulting intensity projection is processed according the flow chart displayed below.

1. Assuming an initial proportionality between the *x* and the z_D coordinate, the intensity modulation provides the second derivative of the longitudinal profile.
2. The integration of the derivative returns a first guess on the profile error. The expected z_D coordinates are computed from the profile error.
3. The histogram of the computed z_D coordinates is compared with the measured intensity profile.
4. The computation is refined by re-sampling the intensity profile over the z_D coordinates. The profile converges in about 20 iterations.



measured intensity, $I(z_D)$

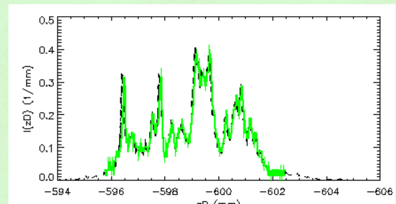
First guess (ideal mirror)

$$x = -\frac{L}{w} z_D$$

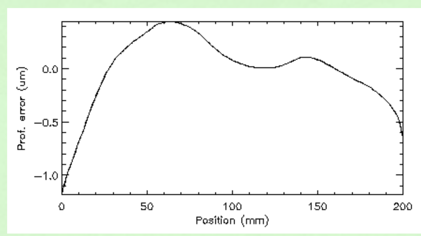
$$z'_m(0) = \sin\alpha$$

Curvature equation (simplified)

$$z''_m(x) = \frac{z'_m(0)}{2D}\left(1 - \frac{I_0}{I(z_D)}\right)$$



Resample $I(z_D)$ over $z_D(x)$



$z_m = z_m(x)$

Refined mirror profile

$z_D(x) = z_m(x) + 2\, z'_m(x)\,(D-x)$

Refined detector mapping

Finally, the computed profiles are assembled into 3D error profiles, shown in **Fig. 8**. The map exhibits the characteristic, expected modulation caused by the presence of the ribs, and the maximum departure from the nominal profile in between.

The error profile has been used to derive the expected optical quality in terms of Point Spread Function (**Fig. 9**), also accounting for the measured surface roughness. The predicted HEW is close to 15 arcsec, a value very close to the HEW computed from direct topography mapping. Measurements in focus – expected in Jan 2014 – should confirm the result.

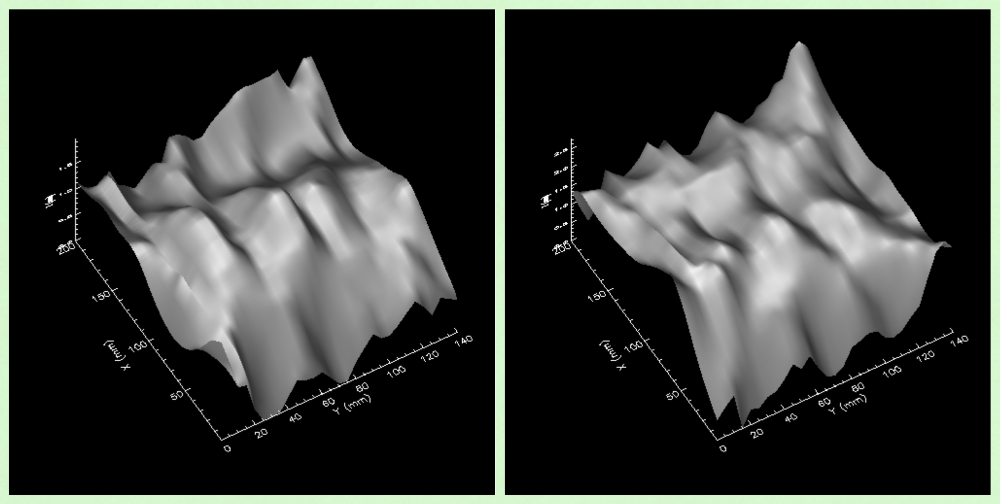


Fig. 8: 3D profile error (shaded map) of the A) parabolic segment and B) the hyperbolic segment of the PP0, as reconstructed from the intra-focal images. The roundness errors were not computed.

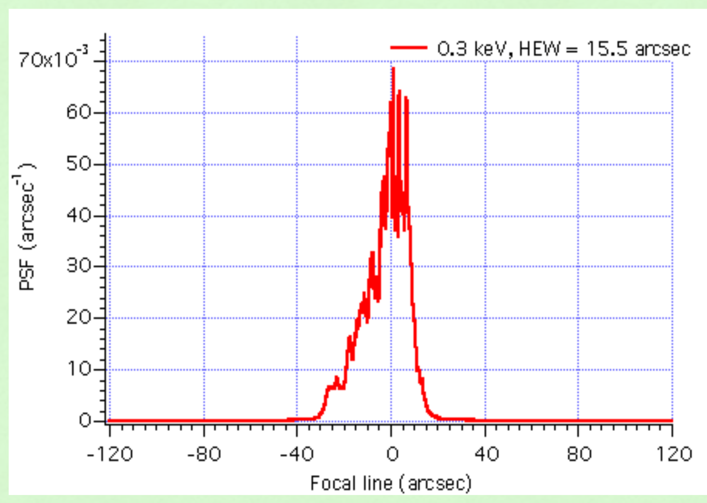


Fig. 9: the predicted PSF at 0.27 keV, as computed from the measured microroughness and the longitudinal profiles reconstructed from the intra-focus images.

4. SUMMARY

We have described a method to directly derive the longitudinal profile of a mirror from a full- illumination, intra-focal, X-ray image, in a similar way, here probably applied for the first time in X-rays (**ref. 4**). Its application requires only a well-collimated, low-divergency X-ray beam and an imaging detector with a good spatial resolution like the ones available at PANTER. The intra-focus image is to be recorded at a quite short distance, to be optimized from case to case, from the mirror under test, and the surface roughness must have a negligible effect at the X-ray energy in use. For this reason, the method can be useful for a sensitive mirror shape diagnostics under X-rays, without the need to remove the mirror from the vacuum chamber to re-measure its profile. In particular, it was possible to determine the angular resolution of the focusing system. For this reason, this approach can be very useful in active X-ray optics applications to derive the mirror shape directly under X-rays, and consequently provide a feedback to the actuator matrix and optimize the mirror shape in real time.

ESSENTIAL REFERENCES

1. M. Civitani, et al., "*Accurate integration of segmented x-ray optics using interfacing ribs*", **Opt. Eng.**, 52(9), 091809 (2013)
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4. D. Spiga et al., "*Profile reconstruction of grazing-incidence X-ray mirrors from intra-focal X-ray full imaging".* **SPIE Proc.** Vol. 8861, 88611F (2013)