Calibration of the Chandra On-Axis PSF

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On-axis PSF

- PSF core ($\lesssim 90\%$ encircled energy)
  - low frequency mirror figure errors; misalignments
- PSF wings
  - scattering from mirror microroughness (high frequency errors)
  - low level (especially at low energies); requires bright source to see wings above background, leading to pile-up for ACIS detectors.

Calibration Aims

- Qualitative
  - PSF shape – “is my source extended?”
- Quantitative
  - PSF as “background”; need accurate subtraction, \textit{e.g.}, extracting an X-ray dust scattering halo.
  - need: shape, absolute normalization, as function of E.
Ground Calibration (XRCF Wing Scans)

Wing Scan Data

- Surface brightness sampled with pinholes
  - $D_{ap} = 1, 4, 10, 20, 35$ mm diameter
  - up to 6 off-axis offsets ($\pm 1, \pm 2, \pm 3$) $D_{ap}$; ($\theta \gtrsim 10''$).
  - isolated quadrants of individual mirror pairs using shutters
  - HRMA tilted to approximate on-orbit graze angles
  - sampled selected mirror-pair quadrants at $0.277$, $1.49$, $4.51$, $5.41$, $6.4$, $8.08$ keV

- mirror-pair/energy combinations (Mirror pair 1 is largest, 6 is smallest):
  - Mirror pair 1: $1.49$, $4.51$ keV
  - Mirror pair 3: $1.49$, $4.51$, $5.41$, $6.4$ keV
  - Mirror pair 4: $1.49$, $4.51$, $5.41$, $6.4$, $8.08$ keV
  - Mirror pair 6: $0.277$, $1.49$, $4.51$, $5.41$, $6.4$, $8.08$ keV
Ground Calibration (XRCF Wing Scans)

Analysis strategy:

- **Evaluate and fit PSD’s (surface roughness functions) for each mirror pair:**
  - evaluate normalized mirror pair surface brightness profiles (for each energy)
  - combine surface brightness data from different energies to estimate the PSD (surface roughness function) vs. roughness spatial frequency for each mirror pair.
  - fit the PSD for each mirror pair

- **Use individual mirror pair PSD fits to evaluate HRMA surface brightness profile; for a given energy:**
  - evaluate the normalized surface brightness profile for the mirror pair
  - add the profiles, weighted by the fraction of total effective area.

- **This procedure allows interpolation to different energies**
Ground Calibration (XRCF Wing Scans)

Figure 1: PSD ($2W_1$) data and fits for individual mirror pairs
Ground Calibration (XRCF Wing Scans)

Figure 2: Model HRMA surface brightness profiles based on mirror pair PSD’s
Ground Calibration (XRCF Wing Scans)

Figure 3: Modeled HRMA surface brightness profile vs. data (E = 1.486 keV)
Ground Calibration (XRCF Wing Scans)

Figure 4: Modeled HRMA surface brightness profile vs. data (E = 6.4 keV)
On-Orbit Data

- obsid 01712: 3C273 on ACIS-S3
  - failed grating insertion
  - \( \sim 30 \text{ ks total, GTI } \sim 15 \text{ ks} \)
  - \( N_{HI} = 1.69 \times 10^{20} \text{ cm}^2 \) (Lockman & Savage 1995, ApJS, 97, 1)

- obsid 01422: LMC X-1 on ACIS-I
  - \( \sim 4 \text{ ks total, GTI } \sim 4 \text{ ks} \)
  - \( N_H \sim 10^{22} \text{ cm}^2; \) 2.9\% dust X-ray halo reported (Predehl & Schmitt 1995, A&A, 293, 889)
  - complex field, e.g. SNR 0540-6944 within a few arcmin (Williams et al. 2000, ApJL, 536, L27)

- obsid 01385: AR Lac on HRC-I
  - \( \sim 19 \text{ ks total, GTI } \sim 19 \text{ ks} \)
  - \( N_{HI} = (5.9 \pm 2.5) \times 10^{18} \text{ cm}^2 \) (Rodonò et al. 1999, A&A, 346, 811)
Figure 5: Surface brightness: 3C273 data (ACIS-S3) vs. HRMA model based on PSD's
On-Orbit: LMC X-1

LMC_X-1 vs XRCF keV (Obsid 1422)

Figure 6: Surface brightness: LMC X-1 data (ACIS-I) vs. HRMA model based on PSD’s
HRMA PSF – Core and Inner Wings

- AR Lac, Obsid 1385

- Note: systematic residual position offsets in HRC event position reconstruction
  - depends on where on the tile the X-ray landed;
  - adds several-pixel blur.
  - overview of some of the issues: M. Juda memo:

- apply an ad-hoc correction for residual HRC position errors:
  - assume AR Lac is a point source
  - aspect residuals are random in direction and uncorrelated.
  - For details of the correction, see the D. Jerius presentation at the Oct. 2001 Calibration Review:
    http://cxc.harvard.edu/cal/calreview/on-axis-psf.ps

- Good agreement between corrected data and raytrace simulation

- Caveats:
  - HRC has very little energy resolution
  - AR Lac is a fairly soft source; tests low energy PSF only
HRMA PSF – Core and Inner Wings

AR Lac [OBSID 1385]

Figure 7: Core and inner wings based on massaged AR Lac HRC data
HRMA PSF $- E \sim 1.5$ keV

Figure 8: low energy surface brightness: $E \sim 1.5$ keV
HRMA PSF Wings - Issues

Issues

- normalization of wings
- need better statistics
- core-wing transition (as a function of energy)
  - core: $\lesssim$ few arcsec
  - wings: $\gtrsim$ 10 arcsec
- ground calibration systematics
  - quad shutter correction; tilt of HRMA; illumination pattern

Plans

- planned calibration observation for wings, either:
  - 100 ks observation of 3C273 on ACIS-l, using very faint mode to further reduce background; $N_{HI} \approx 1.7 \times 10^{20}$ cm$^2$.
  - shorter observation of Her X-1 on ACIS-l, using very faint mode [revised; was: graded mode]; $N_H \approx 10^{20}$ cm$^2$
- far core/near wings
  - search for on-axis intermediate strength sources on ACIS (for energy resolution); less pile-up gets us closer to the core.

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HRMA PSF - Some caveats

Ground Calibration Data (XRCF)

- Backing out ground calibration effects, \textit{e.g.}
  - \textit{Illumination of the optics is different than on-orbit}; this emphasizes the smoother middle portion of the optics $\implies$ expect profiles to somewhat underestimate the wings.
  - Normalization of the data points: assumed an approximate correction for the effects of the quadrant shutters; assumed to be exactly a factor of 2, but could vary depending on off-axis distance and direction (scattering to smaller or larger angles from the optic surface).

- Longer term:
  - \textit{iterative refinement of scattering model} for raytrace to improve agreement with models; this will allow the ground effects & systematics to be backed out more reliably.

Sky data (ACIS)

- Provides an upper limits on wings
  - astrophysical effects (\textit{e.g.}, dust scattering halos) can broaden the PSF; need “clean” lines of sight.

- Systematics, \textit{e.g.:}
  - Depression of inner regions by detector \textit{pile-up} effects.
  - Background subtraction uncertainties; vignetted \textit{vs.} unvignetted background.
  - Evaluation of source rate for \textit{absolute normalization}. 

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