Chandra’s PSF: Use it Wisely

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All you need to know (almost...) 

- The best Astrophysical X-ray mirrors ever made 
- 1" resolution
X-ray optics are unlike most visible optics systems –

they are *grazing* incidence, not *normal* incidence

![Graph showing reflectivity of Ir vs. energy]
X-ray optics are unlike most visible optics systems –

they are *grazing* incidence, not *normal* incidence

Reflectivity of Ir

1° Grazing Incidence

Energy [keV]

Reflectivity
Normal Incidence

Ritchey-Chrétien

http://commons.wikimedia.org/wiki/File:Diagram_Reflector_RitcheyChretien.svg
Grazing Incidence (Wolter–I)

Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter.
Grazing Incidence, A schematic view

- Thermal Precollimator
- Paraboloidal Mirrors
  - MP1
  - MP3
  - MP4
  - MP6
- Central Aperture Plate (CAP)
- Thermal Postcollimator
  - Hyperboloidal mirrors
Peculiarities of Wolter–I Optics

- The projected geometric area is small
- Optics are nested to increase the projected geometric area
- Grazing angles are different for each nested shell, so the energy response differs
- Focal *surface* is not a *plane*, but curved
- Each nested shell has a differently shaped focal surface.
- Good on-axis PSF, degrading off-axis
Outline

1. All you need to know
2. The Hardware
   - Wolter–I Optics
3. Focal Plane & Spectral Response
   - Energy Response
   - Focal Surface
4. PSF
   - 1D
   - 2D
   - Stability
5. Detector Effects
   - ACIS
   - HRC-I
6. Analysis Approaches
7. Resources

Chandra’s PSF

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Total Effective Area ($A_{eff}$)
Fractional contributions of Shells to $A_{\text{eff}}$
Geometric Focal Surfaces

![Graph showing geometric focal surfaces](image)

- **MP1**
- **MP3**
- **MP4**
- **MP6**

**Axis:**
- ΔFocus [mm] — towards mirrors
- Off-Axis Angle [arcmin]
Combined Energy Dependent Focal Surfaces
How do the imaging detectors interact with the focal surface?

... The ACIS-I chips are tilted to approximate the low-energy focal surface.
... The ACIS-S array is curved to match the gratings’ Rowland surface.
... The S3 chip is fairly tangent to the focal surface on-axis.
... HRC-I is tangent to the focal surface on-axis.
ACIS Layout

S0  S1  S2  S3  S4  S5
I0  I1
I2  I3

\{ ACIS-I \}

\{ ACIS-S \}
ACIS Layout
Vignetting

\[
\frac{A_{\text{eff},\Omega}(E, \theta, \phi=[60^\circ,240^\circ])}{A_{\text{eff},\Omega}(E,0,0)}
\]

\[
\begin{align*}
0.010 \text{ keV} \\
0.277 \text{ keV} \\
1.480 \text{ keV} \\
2.020 \text{ keV} \\
2.990 \text{ keV} \\
4.500 \text{ keV} \\
6.300 \text{ keV} \\
7.000 \text{ keV} \\
8.000 \text{ keV} \\
9.000 \text{ keV} \\
9.500 \text{ keV} \\
10.000 \text{ keV}
\end{align*}
\]

Off–axis angle $\theta'$
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On-Axis Enclosed Counts Fraction (ECF)

Low Energies

High Energies

Enclosed Count Fraction

Radius [arcsec]
On-Axis Enclosed Counts Fraction (ECF)
Off-Axis - 85% ECF

![Graph showing the relationship between off-axis angle and semi-major axis for different energies.](image-url)
On-Axis

Ideal Detector (HRC-I pixels)

0.25 keV  0.5 keV  1.0 keV  2.0 keV  3.0 keV
4.0 keV  5.0 keV  6.0 keV  7.0 keV  8.0 keV
Off-Axis: 1.49 keV
Off-Axis: 6.4 keV
There is an anomalous “blob” ∼ 0.6″ from the PSF Core.

http://cxc.harvard.edu/ciao/caveats/psf_artifact.html
PSF Stability

- Chandra is aging, many of its subsystems have changed over time.
- The PSF has in general been quite stable.
- The PSF “artifact” has changed over time, but the recommended analysis removes it from the data.
Impact of Time and Temperature on ECF 90% Radii

Radius = 0.828 Arcsec
Temperature = 69.86 F

Radius = 0.868 Arcsec
Temperature = 70.36 F

All data shown are calculated using "AR Lac" observations.

Data courtesy of Diab Jerius (SOT)
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Pileup (Mrk 421 OBSID 1714)
Pileup: Definition

Pileup occurs when 2 or more photons arrive in a $3 \times 3$ detect island in a single ACIS frame.
Pileup: Effects

Pileup results in:

- Spectral distortion
  - 2 photons → 1 event with higher energy
- Grade distortion
  - merging charge clouds morph “good” events → “bad” ones
  - loss of event

Pileup affects the PSF via:

- Loss of events in dense regions of PSF → craters
- grade morphing, which confuses Energy-Dependent Sub-pixel Event Reconstruction (EDSER)
HRC-I: Ghosts

HRC-I artifacts (ghost “jets”) are *usually* filtered out of \textit{evt2} files, but residues may remain for bright sources

\textbf{evt1: pre-filtering} \hspace{1cm} \textbf{evt2: post-filtering}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ar_lac.png}
\caption{AR Lac (OBSID 13182)}
\end{figure}
HRC-I: Bright source PSF broadening

Some events have an additional blur component if they:

- occur less than \( \approx 50 \) msec after their preceding event
- are physically proximate to the preceding event

![Graph showing 85% Enclosed Count Radius vs. time difference (\( \delta t \)).]
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Overview

The *Chandra* PSF is

- ... marvelous
- ... complex
- ... marvelously complex

- It varies with energy and source off-axis and azimuthal position
- The detectors don’t necessarily follow the focal surface
- The detectors aren’t perfect
- The optics aren’t perfect
Skepticism

To best use it:

- Be Skeptical
- Understand the vagaries of the PSF
- Understand how the detectors interact with it
- Be sure that structure is real.

Simulate, Simulate, Simulate
**Example: Low-count confusion**

Jet?
Multiple Sources?
No! Off-axis point source.
Analysis Approaches

Simulation Tools

- **MARX**
  - a first-order model of the mirrors
  - models of the HRC and ACIS detectors
  - models of the HETG and LETG gratings
  - point and extended sources
  - can use as-observed telescope aspect
  - can use SIMPUT MARX $\geq 5.3.1$

- **SAOTrace**
  - a detailed model of the mirrors
  - point and extended sources
  - can use as-observed telescope aspect

It relies on **MARX** or the CIAO `psf_project_ray` tool to model detectors.
Simulation Tools, con’t

- ChaRT
  - web front-end to SAOTrace
  - can use as-observed telescope aspect
  - point sources only
Quantitative Analysis Techniques

- Monte-Carlo simulations of observations
  - sensitivity analysis of source parameters
  - explore systematics in system models
- 1D and 2D Source fits
  - CIAO provides sherpa fitting package

But...

- The models are not perfect
- Understand the limitations of the Optic and Detector models
How good are the models?

SAOTrace
- Backed by ground calibration
- 1D model good to $\sim 10''$
- Still working on PSF wings (beyond $\sim 10''$)
- 2D model qualitatively correct
- $A_{\text{eff}}$ & Vignetting correct

MARX Detectors
- Semi-emperical
- Not physics-based
Qualitative Analysis Techniques

- **ACIS Sub–pixel Event Reconstruction (EDSER)**
  - uses ACIS event grades to improve image resolution
  - on by default in standard products
  - not calibrated
  - use to identify interesting structure; use non-EDSER data for quantitative measurements

- **Deconvolution**
  - **CIAO** provides Lucy-Richardson via `arestore`.
  - use SAOTrace (or ChaRT) simulations
  - does not preserve flux; use to identify interesting structure; use non-EDSER data for quantitative measurements
  - Not everything you see is real.

- **Adaptive Smoothing**
  - **CIAO** provides `csMOOTH`, `dmimgadapt`.
  - does not preserve flux; use to identify interesting structure; use non-EDSER data for quantitative measurements
  - Not everything you see is real.
What’s Possible

CH Cyg

X-ray w/ HST Contours

X-ray w/ VLA 5GHz Contours

Resources

- PSF Central
  http://cxc.harvard.edu/ciao/PSFs/psf_central.html
- Calibration web site
  http://cxc.harvard.edu/cal/
- Calibration Workshop Presentations
  http://cxc.harvard.edu/ccr/
- CIAO Imaging Threads and Guides
  http://cxc.harvard.edu/ciao/threads/imag.html
- CXC Help Desk
  http://cxc.harvard.edu/helpdesk/
- Others have done this before.
  Check the literature, especially if you’re trying something tricky
  - WebChaser
    http://cda.harvard.edu/chaser/
  - Chandra Data Archive bibliography search
    http://cxc.harvard.edu/cgi-gen/cda/bibliography