Summary of the Recent Update to the *Chandra* HRMA Calibration

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Calibration Review 2009
Overview

- $A_{\text{eff}}$ updated to version N0008; 2009-01-21; part of CALDB 4.1.1
- overview: calibration approach
- previous model (N0007)
- cross-calibration (and *internal*) discrepancies
  $\Rightarrow$ prompted reevaluation of $A_{\text{eff}}$
- evidence leading to model N0008
- testing the new model
Introduction

Impractical to calibrate vs $E, (\theta, \phi), \ldots$ directly:
Sparse datasets (energies, off-axis angles, aperture sizes)

- The *Chandra* mirror $A_{\text{eff}}$ is a semi-analytic model:
- Physics-based where possible
- Raytrace + Ground Calibration Data
Introduction

Impractical to calibrate vs $E, (\theta, \phi), \ldots$ directly:
Sparse datasets (energies, off-axis angles, aperture sizes)

- based on detailed raytrace model
  - figure, geometry, misalignments
  - surface properties: shape (deformations) and microroughness (scattering)
  - measured reflectivity properties (Ir optical constants)
  - as-measured as-built where possible
  - raytrace model (and calibration) is per-shell
 add up four shells to get full HRMA
Introduction

Impractical to calibrate vs $E, (\theta, \phi), \ldots$ directly:
Sparse datasets (energies, off-axis angles, aperture sizes)

- **Ground Calibration Data**
  - sparse datasets (energies, off-axis angles, pinhole sizes)
  - not enough to fully constrain $A_{eff}$
  - used to verify raytrace models.

- **Ground calibrations measured $A_{eff}$ with two detectors**
  - **FPC:** flow proportional counter
    - various pinholes up to 35mm diameter
  - **SSD:** solid state detector, 2mm diameter pinhole
    - mainly 2mm diameter pinhole
  - FPC and SSD: line and continuum sources
Introduction

Impractical to calibrate vs $E, (\theta, \phi), \ldots$ directly:
Sparse datasets (energies, off-axis angles, aperture sizes)

- Ground calibration models did not reproduce the detailed shape of raytrace $A_{\text{eff}}$.
  - discrepancies between detectors; not well understood
  - generated energy dependent correction factor for raytrace
    applied to on-orbit models only
XRCF Model Underlying the Previous CALDB Version

Individual shells - polynomial correction factor

Correct individual shells

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XRCF Shell 1 Effective Area Ratio within 2 mm Aperture

- Scaling Function
- SSB Data/Raytrace Ratio
- PPC Data/Raytrace Ratio

Energy (keV):
- 0
- 2
- 4
- 6
- 8
- 10

Effective Area Ratio (Data/Raytrace):
- 0.70
- 0.80
- 0.90
- 1.00
- 1.10
- 1.20

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XRCF Shell 3 Effective Area Ratio within 2 mm Aperture

- Scaling Function
- SSB Data/Raytrace Ratio
- PPC Data/Raytrace Ratio

Energy (keV):
- 0
- 2
- 4
- 6
- 8
- 10

Effective Area Ratio (Data/Raytrace):
- 0.70
- 0.80
- 0.90
- 1.00
- 1.10
- 1.20

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XRCF Shell 4 Effective Area Ratio within 2 mm Aperture

- Scaling Function
- SSB Data/Raytrace Ratio
- PPC Data/Raytrace Ratio

Energy (keV):
- 0
- 2
- 4
- 6
- 8
- 10

Effective Area Ratio (Data/Raytrace):
- 0.70
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XRCF Shell 6 Effective Area Ratio within 2 mm Aperture

- Scaling Function
- SSB Data/Raytrace Ratio
- PPC Data/Raytrace Ratio

Energy (keV):
- 0
- 2
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Effective Area Ratio (Data/Raytrace):
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- 1.20
XRCF Model Underlying the Previous CALDB Version

Synthesize full HRMA model - add up the shells

HRMA = combined shells

relative weighting

[Graph of XRCF HRMA Effective Area Ratio within 2 mm Aperture]

[Graph of fractional contribution vs. energy]
On-Orbit Discrepancies

$A_{\text{eff}}$ Discrepancy at the Ir edge

- HETG data showed a discrepancy at the Ir edge
- consistent with $\sim 20\text{Å}$ hydrocarbon contamination layer
- Contamination added to on-orbit models
- CALDB 3.2.1 (2005-12-15): new HRMA $A_{\text{eff}}$
  hrmaD1996-12-20axeffaN0007.fits

Cross-calibration (& internal discrepancies)

- Fits for high-T clusters: *Chandra* and *XMM-Newton* discrepant
  - *Chandra* fits showed internal discrepancies for the same clusters
    - Fe K$\alpha$ line vs. continuum
    - prompted reexamination of on-axis $A_{\text{eff}}$
**$A_{\text{eff}}$ Reexamination**

Initial analysis:

- “XRCF Correction” doesn’t account for Ir edges; adding $\sim 20\text{Å}$ contamination layer made Ir edge look better,
- “XRCF Correction” qualitatively has same effect as contamination (away from the edges).
- Did “correction” partially account for contamination already existing on ground?

If so… contamination layer effect $\sim$doubled away from Ir edges.
- Removing the “XRCF Correction” while retaining an $\sim 20\text{Å}$ contamination layer *seemed* to address the inconsistencies within the *Chandra* fits.
- Does *not* completely resolve differences between observatories.
Stability on-orbit

- Flux Contamination Monitor (contamination cover at front of HRMA). ACIS+FCM measurements:
  - just before leaving XRCF
  - before opening contamination cover on-orbit
  - change in effective thickness of hydrocarbon layer $\leq 10\AA$ (Elsner et al., SPIE 4138, 2000)

- analysis of HZ 43 data (Nov 1999 – Jan 2002); upper limit on C contamination thickness change: $\sim 50\AA$ (if at normal incidence) $\Rightarrow \sim 1\AA$ (at grazing incidence); i.e., no significant change since at least shortly after launch. (J. Drake memo).
Contamination on the ground - HETG evidence
HETG continuum measurements; C Anode, Cu Anode (MEG) (from H. Marshall talk)

Consistent with \( \sim 20\text{Å} \) overlayer

If contamination layer was also present in ground testing, how is final on-orbit \( A_{\text{eff}} \) affected?
Vary contamination thickness - shell by shell
Example: (Data/Raytrace) for Shell 1

Example: (Data/Raytrace) for Shell 1 0 Å

[turnup at high E: residual pileup effect]
Vary contamination thickness - shell by shell

Example: (Data/Raytrace) for Shell 1

Example: (Data/Raytrace) for Shell 1 \(22\,\text{Å}\)

[turnup at high E: residual pileup effect]
Vary contamination thickness - shell by shell

Example: (Data/Raytrace) for Shell 1

Example: (Data/Raytrace) for Shell 1 25 Å

[turnup at high E: residual pileup effect]
Vary contamination thickness - shell by shell

Example: (Data/Raytrace) for Shell 1

Example: (Data/Raytrace) for Shell 1 27 Å

XRCF Shell 1 Effective Area Ratio within 2 mm, CH2: 27 Å

Scaling Polynomial Function
SSD Data/Raytrace Ratio
FPC Data/Raytrace Ratio

[turnup at high E: residual pileup effect]
Vary contamination thickness - shell by shell

Example: (Data/Raytrace) for Shell 1

Example: (Data/Raytrace) for Shell 1 30 Å

XRCF Shell 1 Effective Area Ratio within 2 mm, CH2: 30 Å

[turnup at high E: residual pileup effect]
Vary contamination thickness - shell by shell

Example: (Data/Raytrace) for Shell 1

Example: (Data/Raytrace) for Shell 1 40 Å

[turnup at high E: residual pileup effect]
Contamination layer thicknesses: Final Results

Shell 1: 28Å, Shell 3: 18Å, Shell 4: 20Å, Shell 6: 27Å

grey offsets unexplained; largest for shell 1
Combining SSD and FPC data

A new correction factor

- Considered 10 algorithms for combining the FPC, SSD data:
  - none truly horrible
  - a few worse than the rest
  - most pretty comparable

- many tests and much debate → algorithm 1
  Combines lowest order moments of the FPC, SSD data.
  For each shell:
  - mean of FPC data
  - mean SSD data
  - average the averages

- grey correction factors: larger for shell 1
- applied shell by shell to the on-orbit raytrace model
  - HRMA model = \sum \text{single shell models}
  \implies \text{overall HRMA correction is not grey}
  (\approx \text{grey for low } E, \text{nongrey for high } E)
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  ⇒ overall HRMA correction is not grey
    (≈ grey for low \( E \), nongrey for high \( E \))
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- many tests and much debate $\Rightarrow$ algorithm 1
  Combines lowest order moments of the FPC, SSD data.
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- applied shell by shell to the on-orbit raytrace model
  - HRMA model $= \sum$ single shell models
    $\Rightarrow$ overall HRMA correction is not grey
    ($\approx$ grey for low $E$, nongrey for high $E$)
Comparison of Models

- lower panel: deviations from CALDB N0007 model (⇒ flat line)
New HRMA axial effective area (N0008)

Released 2009-01-21 as part of CALDB 4.1.1

Model $f \rightarrow$ HRMA effective area N0008.

Comparison: N0007 vs N0008
New HRMA axial effective area (N0008)

Tests

Numerous tests, including:

- galaxy clusters
- AGNs
- thermal SNR (E0102)
- synchrotron-dominated SNR (G21.5-0.9)
- soft thermal sources

Differences between N0008 and N0007:

- Derived spectral parameters (e.g., kT, $\Gamma$) typically differ less than $\sim 3\%$
- However...
  - kT can be up to $\sim 10\%$ less for hot galaxy clusters
  - soft sources (0.5-2 keV band): derived fluxes can be up to $\sim 8\%$ higher.
New HRMA axial effective area (N0008)

Galaxy Clusters

ACIS: $kT_e$: Fe K$_\alpha$ vs continuum

![Plot showing Fe K$_\alpha$ vs continuum for different models.](image)
New HRMA axial effective area (N0008)

Galaxy Clusters

ACIS: $kT_e$: Fe Kα vs continuum

![Graph showing $kT_e$ vs Fe Line $kT$]
New HRMA axial effective area (N0008)

Galaxy Clusters

ACIS: Hard vs Broad band

![Graph showing ACIS data points for hard and broad bands.]

- CALDB
- MODEL A
- MODEL B
- MODEL C
- MODEL F
New HRMA axial effective area (N0008)

Galaxy Clusters

ACIS vs. MOS: hard band

![Graph showing ACIS vs. MOS for hard band](image)
New HRMA axial effective area (N0008)

Galaxy Clusters

ACIS vs. MOS: broad band
New HRMA axial effective area (N0008)
AGN spectra; Powerlaw sources (fit 0.7-7.5 keV) N0007
(2nd order MEG/HEG correction not applied)
differences between variants statistically insignificant.
New HRMA axial effective area (N0008)

AGN spectra; Powerlaw sources (fit 0.7-7.5 keV) N0008
(2nd order MEG/HEG correction not applied)
differences between variants statistically insignificant.
modest systematic change for parameters; comparable $\chi^2_{\text{red}}$
Summary

- Calibration based on detailed raytrace model plus ground tests
- Many tests, derived spectral parameters comparable (∼3%) except for
  - hot galaxy clusters (kT ≤10% lower)
  - derived fluxes for soft source (∼8% higher).
- New HRMA effective area (N0008) released