IACHEC meeting 2013
NuSTAR in-flight calibration

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NuSTAR

Energy range: 3 – 78.4 keV
Outline

- NuSTAR data diorama part 1
- Detectors
  - RMF
- Optics
  - Physical motivated ray trace model
  - Intermission NuSTAR data diorama part 2
  - PSF
  - ARF
- Background
- Astrometry
NGC 1365

3/26/13
NGC 1068

Model: pexriv+zgauss

March 20, 2013
NGC4151

One of the brightest Seyfert galaxies. Observed last November jointly with Suzaku (141 ks NuSTAR, about 150 ks Suzaku). Main goal: corona temperature

XIS-FI
obs2 FPMA
obs3 FPMA
obs5 FPMA

Summed Spectrum
power-law
broad Fe Kα
cold reflection
photoionized lines

- •
Detector Efficiency

Escape lines
Cd & Te

Detector 0
Detector 1
Detector 2
Detector 3

Energy (keV)
Low-energy Detection Efficiency Drop

5 Crab spectra with different pointings

- FPMA/DET0
  - \( Pt = 0.138 \pm 0.001 \, \mu m \)
- CZT
  - \( CZT = 0.187 \pm 0.009 \, \mu m \)

- <5% uncertainty produced by unknown residuals around 4 keV

Credit: Takao Kitaguchi

3/26/13
Absolute Energy Scale Below 6 keV

- W-SW knot region of Cas A
- Fitting model: PL + Bremss + 4 Gaussians (Ar-Ka, Ca-Ka, Fe-Ka, Fe-Kb)

<table>
<thead>
<tr>
<th>+Ni-Ka)</th>
<th>Line Center Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suzaku/XIS</td>
</tr>
<tr>
<td>Ar-Ka</td>
<td>3.128 -0.004 +0.006</td>
</tr>
<tr>
<td>Ca-Ka</td>
<td>3.890 -0.008 +0.010</td>
</tr>
<tr>
<td>Fe-Ka</td>
<td>6.606 -0.006 +0.007</td>
</tr>
<tr>
<td>Fe-Kb + Ni-Ka</td>
<td>7.731 -0.095 +0.111</td>
</tr>
</tbody>
</table>

- Absolute energy scale accuracy is <50 eV

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- Wolter-I conical approximation
- Focal length = 1015 cm
- 133 shells
- Multilayers (Pt/C, W/Si)
HPD = 59”/57”
FWHM = 18”
Used 7 bright sources to characterize the PSF
Her X-1
GRS1915
Cygnus X-1
Vela X-1
GS0834
PSF Modeling

- Used common PSF parameters for 7 point source observations
- Difference in the enclosed fraction: Data-Model
- Average (and standard deviation) for 7 observations × 2 modules
- ~1% uncertainty for R<60" extraction

Errors in the enclosed fraction were calculated using the model PSF.

Data-Model

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Cas A Imaging

4.5-6 keV

8-10 keV

10-15 keV

15-20 keV

20-25 keV

25-35 keV
Cas A Imaging

Hard Rims
- 4.5-6 keV
- 8-10 keV
- 10-15 keV

Soft interior

Bright knots
- 15-20 keV
- 20-25 keV
- 25-35 keV
De-convolved Crab Image

Chandra

NuSTAR
Physically motivated Raytrace model. (Niels Jørgen Westergaard)

- Geometrical model – obscuration, mirror slopes (LVDT).
- Optical constants – LLNL effort.
- Multilayer parameters (Pt/C, W/Si) – Fitting of witness samples and curved glass pieces, coupled with coating parameters.
- Scattering mechanism – scattering model.
ARF: vignetting functions

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Stray light (zero bounce) and Ghost Rays (single bounce)

- Ghost rays come from sources between 3 and 40 arcmin offaxis.
- Stray light component comes from bright sources roughly between 3 and 6 degrees.
Part of the sky visible thru the aperture stop and not blocked by the optics bench (black) – the blue circles represent the FOV through the aperture stop at the 4 corners of the focal plane and are ~3 degrees in diameter.
ARF corrections: Ghost Rays & Aperture Stop

What are ghost rays?

- Single bounce photons either from the upper mirror (red) or the lower mirror (blue). Double bounce photons are properly reflected and focused photons (black).

Azimuthal, Radial and time dependency

Function of time
ARF corrections: Ghost Rays & Aperture Stop

Detector plane

Aperture plane

3 arcmin

6 arcmin

3/27/13
The Crab Calibration Data Set

**NuSTAR uses the Crab for:**
- Exposure times from 7ks (2 orbits) to 15ks (4 orbits)
- Off-axis angles range from 0.5 to 6 arcminutes.
- Minimum 2 pointings on each detector

**NuSTAR uses the Crab for:**
- Effective Area calibrator
- Internal normalization calibrator – detector to detector
- Optical Axis calibrator
- RMF calibrator
- (Timing calibrator)
Progression since launch

Module A = FM2

Launch responses

Module B = FM1

Launch responses

Module A = FM2

New responses

Module B = FM1

New responses

3/26/13
Crab

\[ \Gamma = 2.1 \]
\[ N = 10 \]
**Calibration Path forward**

- **Model ARF**
  - Optical constant improvements
  - Multilayer phase space search

- **Crab corrected ARF**
  - Robustness of method: test case 3C273, G21.5+0.9
  - Goal: Rectifying ARF and vignetting files with Crab corrected curves
  - Still need to decide on exact model parameter.
Background
Part of the sky visible thru the aperture stop and not blocked by the optics bench (black) – the blue circles represent the FOV through the aperture stop at the 4 corners of the focal plane and are ~3 degrees in diameter.
Cosmic X-ray Background (CXB)

“Nominal” optical axis position
Spectral Model of CXB
Additional “aperture” flux component: Galactic X-ray Ridge Emission (GXRE)

Spatial variation has a different shape based on the assumed spatial model of the GXRE.

Only important near galactic plane (<20 degrees latitude).

Top: Model of GXRE for G21.5

Bottom: Model of CXB for G21.5
Astrometry
• Reconstruction challenge is to take out thermally driven motion of the benches ~ few mm to better than ~200 microns.

• Lasers plus CHU-4 register bulk bench motion.

• Relative motion of lasers, metrology detectors, CHU-4 with respect to bench is not measured.
Registering the benches

- Metrology traces typically range +/- 1 to 2 mm
Pointing does not affect reconstruction but can influence PSF!

Module A

Det X (mm)

8.3650×10^7 8.3652×10^7 8.3654×10^7 8.3656×10^7 8.3658×10^7 8.3660×10^7 8.3662×10^7 8.3664×10^7

seconds

Module A

Det Y (mm)

8.3650×10^7 8.3652×10^7 8.3654×10^7 8.3656×10^7 8.3658×10^7 8.3660×10^7 8.3662×10^7 8.3664×10^7

CHU-2
Absolute astrometry bounded by +/-7.5” in X, Y \( \rightarrow 10” \) total with all points. Excluding 2 sources \( \rightarrow 7” \) total
Delta X vs Day of Mission

Delta X (mm)

Day of Mission
Delta Y vs Day of Mission

![Graph showing Delta Y vs Day of Mission](image-url)
Summary

- **Detectors**
  - RMF
    - Good condition, ~5%

- **Optics**
  - ARF
    - 5 – 35 keV, ~5%
    - 35 – 40 keV, ~7-10%
    - 40 – 80 keV, ~30%
  - PSF
    - EEF, ~2%

- **Background**
  - Complex, but manageable

- **Astrometry**
  - +/- 10” – Goal +/- 5”
Any Questions?