PSF in-flight calibration
for MOS 1 and MOS 2 cameras

Simona Ghizzardi
Silvano Molendi
OVERVIEW

- The data set
- The analysis procedure
  - Building the radial profile
  - A model for the PSF
  - Fitting the radial profile
- Results
### THE DATA SET

**ENERGY RANGES:**

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Range (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>[200-400]</td>
</tr>
<tr>
<td>0.6</td>
<td>[400-800]</td>
</tr>
<tr>
<td>1.0</td>
<td>[800-1200]</td>
</tr>
<tr>
<td>1.8</td>
<td>[1200-2400]</td>
</tr>
<tr>
<td>3.7</td>
<td>[2400-5000]</td>
</tr>
<tr>
<td>6.5</td>
<td>[5000-8000]</td>
</tr>
<tr>
<td>10.0</td>
<td>[8000-12000]</td>
</tr>
</tbody>
</table>

### SOURCES:

**ON-AXIS**

- CAPELLA  EXO0748-67  3C273
- GX13+1   HR1099     PKS0558
- LMC X-3  PKS0312    PSR0540

**OFF-AXIS** (> ~ 2 arcmin)

- HR1099   6.44 (arcmin)
- CAPELLA  9.00; 4.48
- (Capella) 9.48
- GX13+1   5.53; 9.00; 9.18; 1.92
- (GX13+1) 11.89; 2.74; 6.26
- 3C273    6.31; 1.55
- PSR0540  9.83
- (HCG016) 11.52
- (LMC)    11.9; 5.63
- OMC2/3   0.34 --> 10.44
FOR EACH MOS

• we merged the observations having
  • the same source target
  • the same pointing position
  • different filters and/or operative mode --->
    ---> different pile-up levels

• The centroid is determined accounting
  • for the mask of the detector

• For each curve a good fitting range
  • must be defined (points suffering
    • for pile-up must be excluded).
Algorithm for the averaged radial profile

- Energy selection and pattern (0-12) selection

**BASIC METHOD**

We bin the image (with larger bins at larger radii)

RADIAL PROFILE: \( \frac{dN}{dA} \) (the area is not \( 2\pi rd \) because of the mask)

- each (squared) pixel is assigned to the (round) bin to which its CENTER belongs

- for these pixels it works fairly

- these pixels belong to two different bins in comparable fractions

- the effect is less important at larger radii

**ADDITIONAL RECIPE ADDED TO THE BASIC PROCEDURE**

We enclose each pixel in a circle.

If the circle is **fully** enclosed in the bin then the pixel is too.

If the circle is **partly** enclosed in another bin, the pixel may belong to two bins: *we divide such pixels in NSUBPIXELS*
A Model for the PSF

- we want an analytical function to describe the PSF
- according to the ground calibration results (FM1)
  \[ \text{PSF} = \text{KING} + \text{GAUSS} \]
- In orbit PSF
  \[ \text{PSF} = \text{KING} + \text{GAUSS} + \text{BKG} \]

BKG in the data is high and Gauss component becomes negligible. Fitting is Gauss parameters-insensitive.

- Data often suffer of pile-up. The King slope is well sampled but a large set of data is not useful for the core radius.
King profile

King = \frac{A}{\left[1 + \left(\frac{r}{r_c}\right)^2\right]^\alpha}

Two shape parameters: core radius and slope.

IT CAN BE INTEGRATED ANALYTICALLY IN rdr!!!
Fitting the radial profiles

In order to enhance the statistics, we fit simultaneously the different curves with different pile-up levels

\[ \text{PSF} = \text{King} + \text{BKG} \]

\( \alpha \) e \( r_c \) are the same for the different curves

BKG and the normalization are different for each curve

for each energy and off-axis angle we derive \( \alpha \) and \( r_c \).
FOR FIXED OFF-AXIS

\[ r_c = r_c(E, \theta) \]

\[ \alpha = \alpha(E, \theta) \]

**CORE RADIUS:**

tends to decrease when energy increases (LINEAR).

**SLOPE:**

the slope is roughly constant with energy (slightly decreasing - LINEAR).

**OFF-AXIS** = 0.15 (arcmin)

At higher off-axis angles few data are available.
FOR FIXED OFF-AXIS

\[ r_c = r_c(E, \theta) \]
\[ \alpha = \alpha(E, \theta) \]

CORE RADIUS:

tends to decrease when energy increases (LINEAR).

SLOPE:

The slope is roughly constant with energy (slightly decreasing - LINEAR).

OFF-AXIS = 5.66 (arcmin)

At higher off-axis angles few data are available.
FOR FIXED OFF-AXIS

\[ r_c = r_c(E, \theta) \]
\[ \alpha = \alpha(E, \theta) \]

CORE RADIUS:
- tends to decrease when energy increases (LINEAR).

SLOPE:
- The slope is roughly constant with energy (slightly decreasing - LINEAR).

OFF-AXIS = 11.89 (arcmin)

At higher off-axis angles few data are available.
FOR FIXED OFF-AXIS

\[ r_c = r_c(E, \dot{\theta}) \]
\[ \alpha = \alpha(E, \dot{\theta}) \]

**CORE RADIUS:**
- Tends to decrease when energy increases (LINEAR).

**SLOPE:**
- The slope is roughly constant with energy (slightly decreasing - LINEAR).

**OFF-AXIS = 0.25 (arcmin)**

At higher off-axis angles few data are available.
FOR FIXED OFF-AXIS

\[ r_c = r_c(E, \theta) \]
\[ \alpha = \alpha(E, \theta) \]

CORE RADIUS:

tends to decrease when energy increases (LINEAR).

SLOPE:

the slope is roughly constant with energy (slightly decreasing - LINEAR).

OFF-AXIS = 1.72 (arcmin)

At higher off-axis angles few data are available.
FOR FIXED OFF-AXIS

\[ \rho_c = \rho_c(E, \vartheta) \]
\[ \alpha = \alpha(E, \vartheta) \]

CORE RADIUS:

tends to decrease when energy increases \( (\text{LINEAR}) \).

SLOPE:

the slope is roughly constant with energy \( (\text{slightly decreasing - LINEAR}) \).

OFF-AXIS = 10.42 (arcmin)

At higher off-axis angles few data are available.
FOR FIXED ENERGY

\[ r_c = r_c(E, \theta) \]
\[ \alpha = \alpha(E, \theta) \]

CORE RADIUS:

is roughly constant
with off-axis angle (LINEAR).

SLOPE:

is roughly constant
with off-axis angle (LINEAR).

At higher off-axis angles few data are available.
At higher energies few data are available.

ENERGY = 1.0 keV

IFC/CNR

Milano, November 7th, 2001
FOR FIXED ENERGY

\[ r_c = r_c(E, \theta) \]

\[ \alpha = \alpha(E, \theta) \]

CORE RADIUS:

is roughly constant

with off-axis angle (LINEAR).

SLOPE:

is roughly constant

with off-axis angle (LINEAR).

At higher off-axis angles few data are available.

At higher energies few data are available.

ENERGY = 3.7 keV
FOR FIXED ENERGY

\[ r_c = r_c(E, \theta) \]
\[ \alpha = \alpha(E, \theta) \]

CORE RADIUS:

is roughly constant
with off-axis angle (LINEAR).

SLOPE:

is roughly constant
with off-axis angle (LINEAR).

At higher off-axis angles few data are available.
At higher energies few data are available.

ENERGY = 6.5 keV
**FOR FIXED ENERGY**

\[ r_c = r_c(E, \theta) \]

\[ \alpha = \alpha(E, \theta) \]

**CORE RADIUS:**

*is roughly constant*

*with off-axis angle (LINEAR).*

**SLOPE:**

*is roughly constant*

*with off-axis angle (LINEAR).*

---

*At higher off-axis angles few data are available.*

*At higher energies few data are available.*
**FOR FIXED ENERGY**

\[ r_c = r_c(E, \theta) \]
\[ \alpha = \alpha(E, \theta) \]

**CORE RADIUS:**

- is roughly constant
- with off-axis angle (LINEAR).

**SLOPE:**

- is roughly constant
- with off-axis angle (LINEAR).

At higher off-axis angles few data are available.
At higher energies few data are available.

**ENERGY = 3.7 keV**
FOR FIXED ENERGY

\[ r_c = r_c(E, \vartheta) \]
\[ \alpha = \alpha(E, \vartheta) \]

CORE RADIUS:

is roughly constant

with off-axis angle \((\text{LINEAR})\).

SLOPE:

is roughly constant

with off-axis angle \((\text{LINEAR})\).

At higher off-axis angles few data are available.
At higher energies few data are available.

ENERGY = 6.5 keV
FOR FIXED ENERGY

\[ r_c = r_c(E, \hat{\theta}) \]
\[ \alpha = \alpha(E, \hat{\theta}) \]

CORE RADIUS:

is roughly constant

with off-axis angle (LINEAR).

SLOPE:

is roughly constant

with off-axis angle (LINEAR).

At higher off-axis angles few data are available.

At higher energies few data are available.

No data for high ENERGIES AND OFF-AXIS ANGLES.

No calibration is possible for these values.

ENERGY = 6.5 keV

IFC/CNR

Milano, November 7th, 2001
2 DIMENSIONAL FIT

\[ r_c = a + b \cdot E + c \cdot \theta + d \cdot E \cdot \theta \]

\[ \alpha = x + y \cdot E + z \cdot \theta + w \cdot E \cdot \theta \]
PSF in-flight calibration - MOS 1 - MOS 2

King Core Radius for MOS 1

CORE RADIUS OF THE PSF - MOS 1

energy (keV)

off-axis (mm)

energy (keV)
King Slope for MOS 1
2 DIMENSIONAL FIT

\[ r_c = a + b \cdot E + c \cdot \theta + d \cdot E \cdot \theta \]

\[ \alpha = x + y \cdot E + z \cdot \theta + w \cdot E \cdot \theta \]

<table>
<thead>
<tr>
<th>( r_c )</th>
<th>MOS 1</th>
<th>( \alpha )</th>
<th>MOS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>5.074 ± 0.001</td>
<td>( x )</td>
<td>1.472 ± 0.003</td>
</tr>
<tr>
<td>( b )</td>
<td>-0.236 ± 0.001</td>
<td>( y )</td>
<td>-0.010 ± 0.001</td>
</tr>
<tr>
<td>( c )</td>
<td>0.002 ± 0.001</td>
<td>( z )</td>
<td>-0.001 ± 0.002</td>
</tr>
<tr>
<td>( d )</td>
<td>-0.0180 ± 0.0006</td>
<td>( w )</td>
<td>-0.0016 ± 0.0013</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( r_c )</th>
<th>MOS 2</th>
<th>( \alpha )</th>
<th>MOS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>4.759 ± 0.018</td>
<td>( x )</td>
<td>1.411 ± 0.001</td>
</tr>
<tr>
<td>( b )</td>
<td>-0.203 ± 0.010</td>
<td>( y )</td>
<td>-0.005 ± 0.001</td>
</tr>
<tr>
<td>( c )</td>
<td>0.014 ± 0.017</td>
<td>( z )</td>
<td>-0.001 ± 0.002</td>
</tr>
<tr>
<td>( d )</td>
<td>-0.0229 ± 0.0133</td>
<td>( w )</td>
<td>-0.0002 ± 0.0011</td>
</tr>
</tbody>
</table>
$r_c$ and $\alpha$ are fixed to the best fit parameters.

The normalization and the background are free parameters.
$r_c$ and $\alpha$ are fixed to the best fit parameters.

The normalization and the background are free parameters.
**Range of Application**

- **Green**: Calibration here is well sampled and the modelization provides a good description of the PSF.
- **Yellow**: Few scattered data with large errors are available here. The modeled PSF must be used with caution.
- **Red**: No data are available here. No calibration is possible in this region. **DON'T USE THE MODEL FOR THESE VALUES.**
**PSF in-flight calibration - MOS 1 - MOS 2**

**ENCIRCLED ENERGY FRACTION**

**EEF IS ANALYTICAL**

Radii enclosing 50% and 80% of the energy at 1.5 keV, 8 keV, 9 keV for the on-axis PSF.

<table>
<thead>
<tr>
<th>MOS 1</th>
<th>R(50%)</th>
<th>R(80%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 keV</td>
<td>8 keV</td>
<td>9 keV</td>
</tr>
<tr>
<td>8.6''</td>
<td>6.7''</td>
<td>6.4''</td>
</tr>
<tr>
<td>24.5''</td>
<td>21.5''</td>
<td>20.9''</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MOS 2</th>
<th>R(50%)</th>
<th>R(80%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 keV</td>
<td>8 keV</td>
<td>9 keV</td>
</tr>
<tr>
<td>9.1''</td>
<td>7.0''</td>
<td>6.6''</td>
</tr>
<tr>
<td>27.7''</td>
<td>23.1''</td>
<td>22.3''</td>
</tr>
</tbody>
</table>

**EEF also for piled-up sources.**

*IFC/CNR*  
*Milano, November 7th, 2001*
**SUMMARY**

• An analytical model for the PSF and the EEF has been provided

• Using a wide set of data, the best fit parameters are provided as functions of the energy and of the off-axis angle.

• A range of application of the model is defined:

  • At high energies and off-axis angles no calibration is possible.

  • The model must be used with caution at intermediate energies/off-axis angles

• Full detailed report available at

  http://www.ifctr.mi.cnr.it/~simona/PSF_inorbitMOS.ps

**NEXT PN !**