EPIC Calibration

Michael Smith, on behalf of XMM-Newton SOC and Instrument Teams

24th XMM-Newton Users' Group Meeting, 10 May 2023

EPIC calibration recommendations from the 2022 UG

- **2020-06-08/09:** The UG recommends to continue the investigations into the pn empirical RMF modelling (e.g., expand to energies >1.7 keV, include other modes, epochs, and spatial regions) and incorporate the outcome into SAS.
- **2020-06-08/10:** The UG recommends to implement the spatial and temporal refinement of the pn energy scale as presented in Sanders et al. (2020, A&A 633, 42) as a calibration product.
- **2020-06-08/11:** The UG recommends to continue the investigations into the off-axis flux calibration of the EPIC cameras.
- **2021-06-10/09:** The UG recommends to finalize the analysis of the possibility of a column by column rate-dependent PHA correction of pn in Burst and Timing modes and publish the conclusions.
- **2021-06-10/10:** The UG recommends to continue to improve the MOS redistribution and determine the impact any improvement has on the MOS-to-PN cross calibration at low energies.
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- **2022-05-17/04:** The UG strongly supports and recommends the production of an analysis guide for observation specific rate-dependent PHA correction (for the PN Burst & Timing modes).
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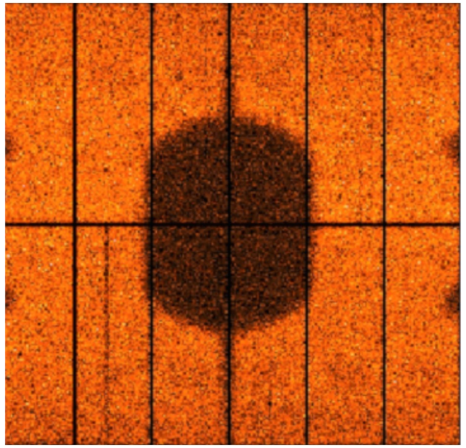
- **2022-05-17/06:** The UG recommends to verify the pattern fractions determined from in-orbit data with the expected pattern fractions
- **2022-05-17/07:** The UG recommends the creation of proton response matrices and to make them available through SAS

Refinement of PN energy scale

Spatial and temporal refinement of the PN energy scale (Sanders et al. A&A 633, 2020):

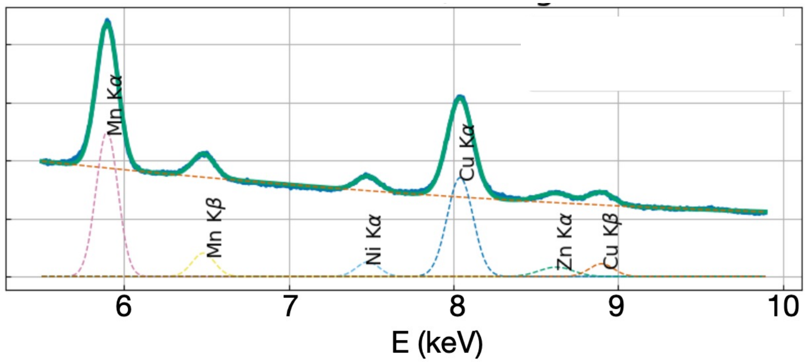
increased accuracy to ~ 150 km/s (from ~ 550 km/s) @ Fe K

Cu Kα emission (8.0 keV)



Aim is to implement this for FF and EFF modes as calibration product (in collaboration with the MPE group)

Refinement consists of three steps:



Step 1. CCD averaged time-dependent correction at Cu Kα

- ✓ XMM-CCF-REL-389 (I. Valtchanov), released March 2022

Step 2. Spatial correction (epoch dependent) at Cu Kα

- ✓ XMM-CCF-REL-391 (I. Valtchanov), released October 2022 (req. SAS 21)

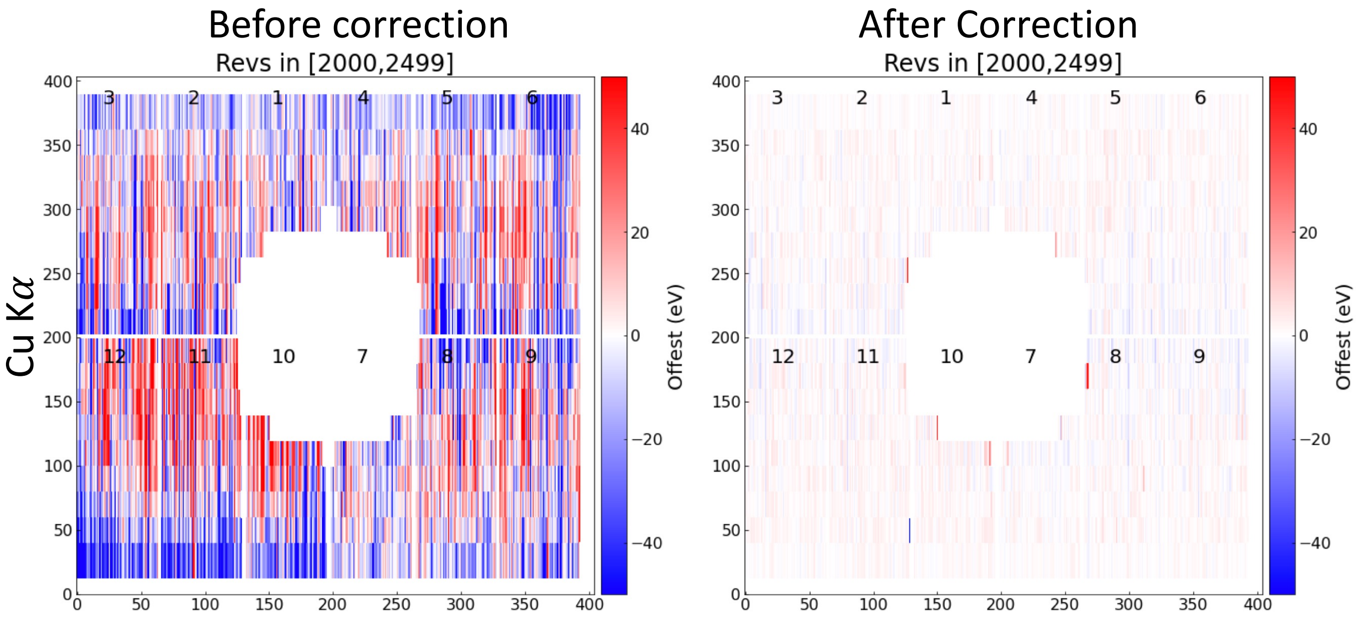
Step 3. Further energy scale refinement using additional instrumental lines (6 - 9 keV)

- ○ Not implemented

Refinement of PN energy scale

Step 2. Spatial correction (epoch dependent) at Cu Kα

- Apply the per-CCD long-term CTI correction for Cu Kα ("Step 1")
- Stack event lists in bins of 500 revolutions, with step 250 (overlap)
- For each stacked table, extract spectra for each CCD, RAWX (64) and in bins of 20 pixels on RAWY
- Fit the Cu Kα line and derive the residual the spatial offsets as function of epoch, CCDNR, RAWX and RAWY segment



Refinement of PN energy scale

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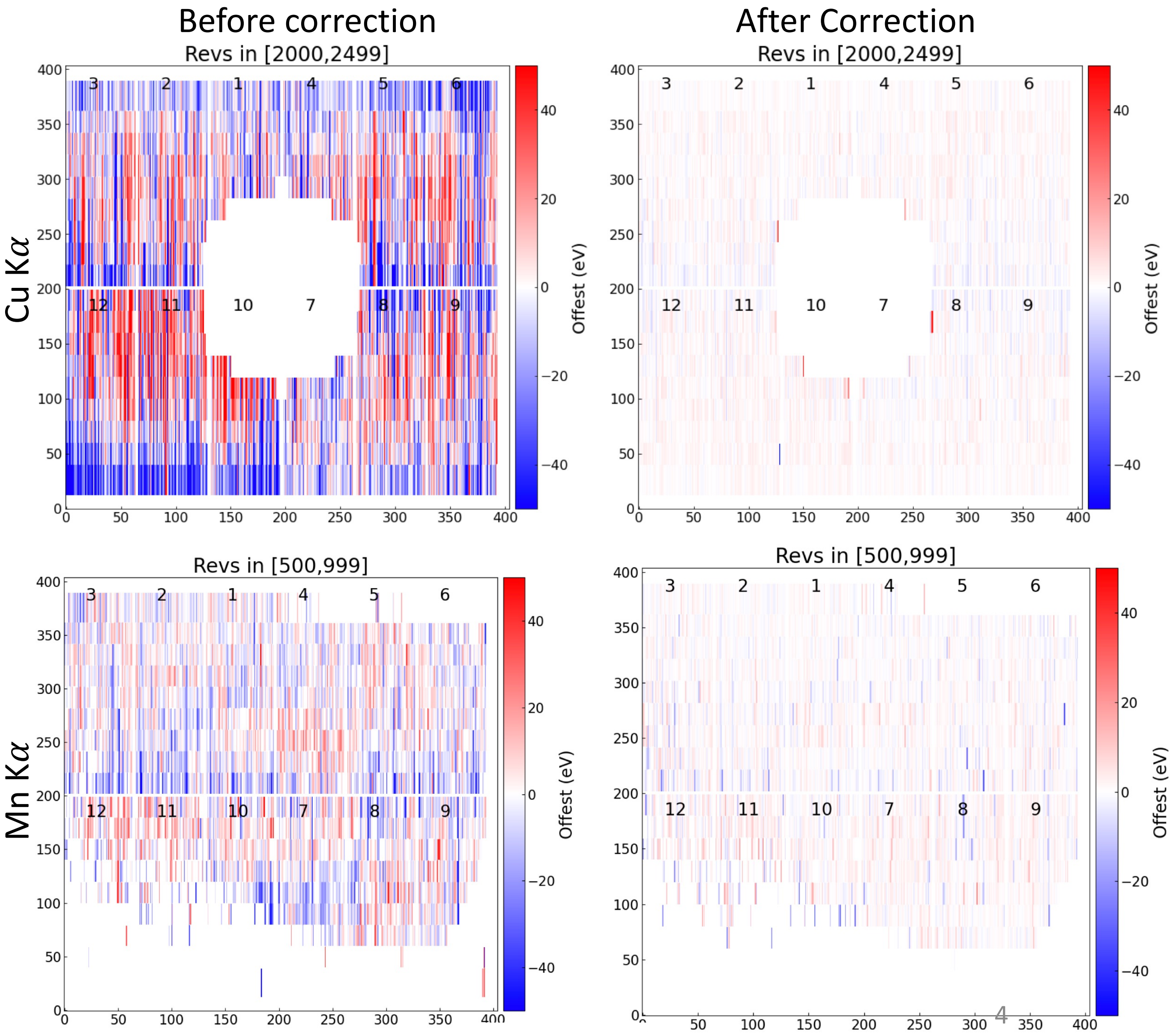
In addition, a similar spatial/time dependent correction was derived at Mn Kα (5.9 keV) using cal source measurements (FF mode only)

✓ XMM-CCF-REL-391 (I.Valtchanov), released Oct 2022

✓ SAS task **`epspatialcti`** (SAS 21)

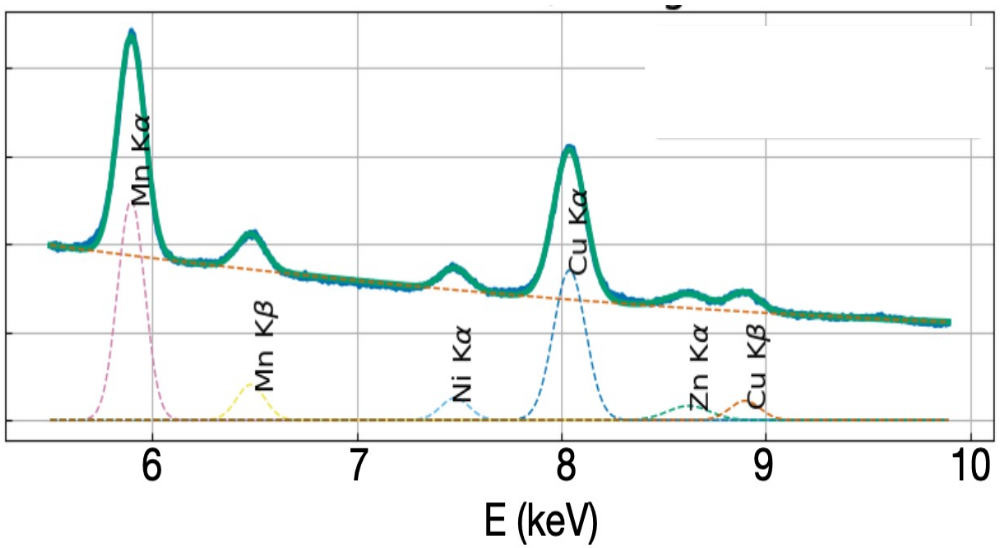


Refinement of PN energy scale

Step 3. Further refinement of the energy scale using the instrumental lines around Cu Kα: time-dependent stretch/compression

- The remaining residuals to be corrected are small (<= 10 eV)
- They are discrepant with Sanders results (in offset and temporal behaviour); also method used is not fully clear
- Avoid introducing unexpected effects

At this point, no strong justification for implementing this step.



Consolidation of PN energy scale calibration

Fully incorporate energy scale calibration at Cu Kα with that at Al Kα and Mn Kα

Scope for improving the two main components affecting time-dependency:

- long-term CTE degradation

- quiescent background dependent gain correction
  - additional data point in E-space
  - additional solar cycle’s worth of data

Still work in progress…

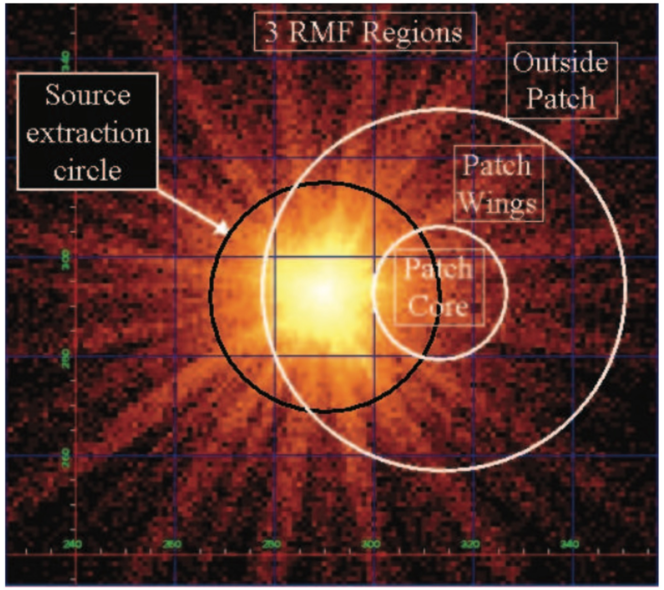
PN empirical RMF modelling

EPIC-pn empirical RMF modelling (K. Dennerl, MPE):

- So far work has concentrated on low E response, for SW mode data
- Expand beyond 1.7 keV, include other modes, epochs, spatial regions
- No progress to report specifically for EPIC-pn
- However, technique is progressing, ARFs and RMFs successfully applied to eROSITA
- Near future: combine EPIC-pn and eROSITA

Work in progress...

MOS contamination and redistribution



MOS cameras show time dependent changes in response due to

- contamination (A_{eff} change < ~ 1 keV)
- spatially dependent redistribution
  - patch core: r<14”
  - patch wings: 14<r<36”
  - off-patch: r> 40”

  where main photo peak “shoulder” flattens into a “shelf” in patch

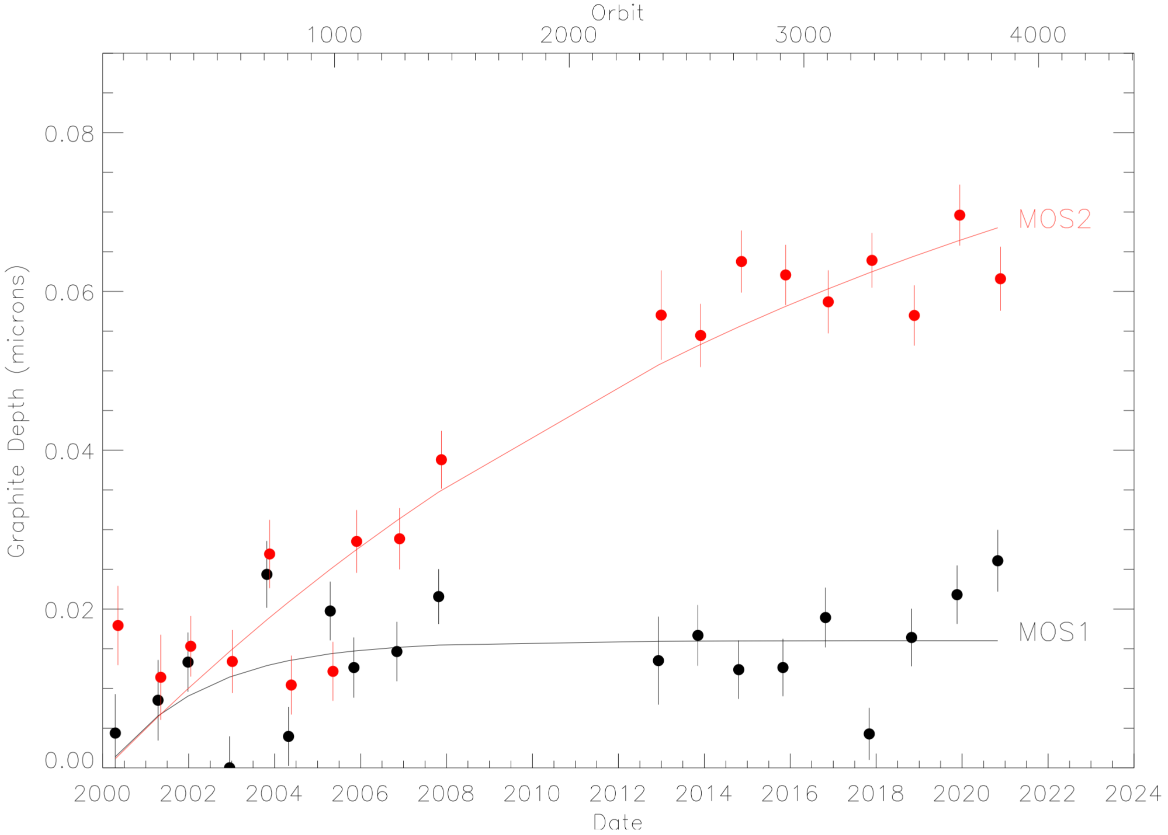
Are corrected for in calibration (contaminant model; epochal & spatially dependent RMFs) but need periodic updates. Previous major updates were in 2013.

Degeneracy: a given RMF solution is dependent on the A_{eff}. Current methodology:

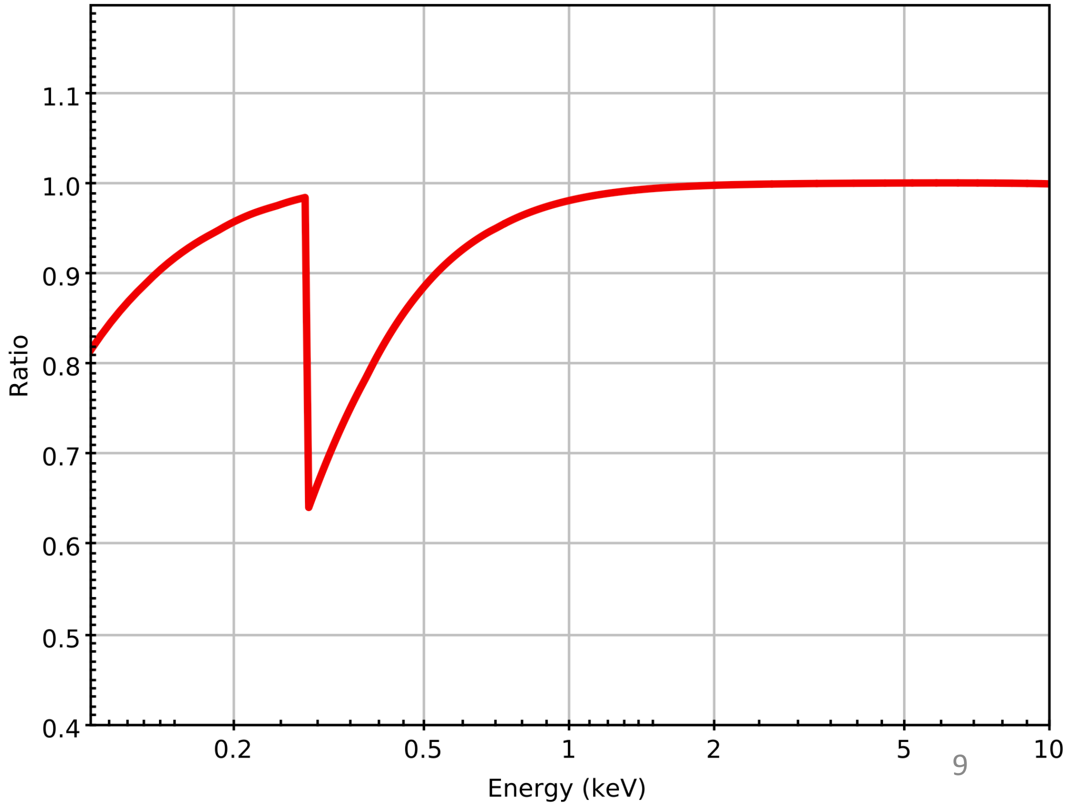
1. Update contaminant model (off-patch data from SNR 1E 0102)
   ✓ XMM-CCF-REL-390 EPIC MOS contamination (S. Rosen et al.), released October 2022
2. Update RMF based on new A_{eff} estimate
   ✓ XMM-CCF-REL-396 EPIC MOS response (S. Rosen et al.), released March 2023

MOS contamination and redistribution

- Measurement of contaminant based on off-patch observations of SNR 1E0102-7219
- Modelled as pure C
- Depth determined by the ratio of observed count rates in 0.1 - 0.75 keV and 0.98 - 3.0 keV bands
- Depth as function of time modelled by an exponential (MOS2)



Ratio of the MOS2 effective area curves from revolutions 3652 (~2019) and 1082 (~2005)



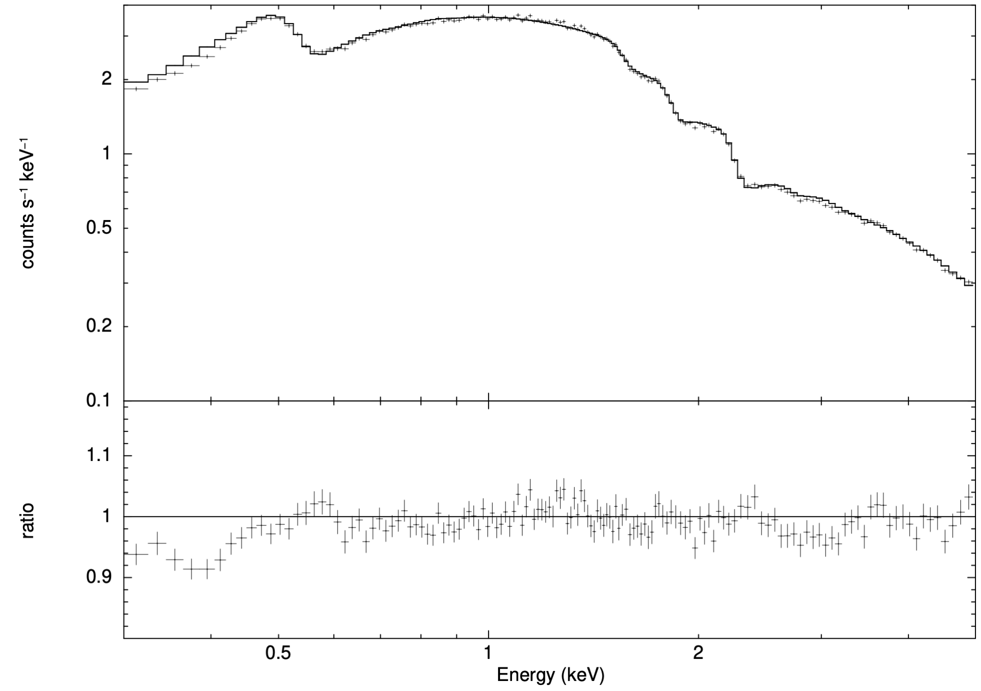
S.Rosen

MOS contamination and redistribution

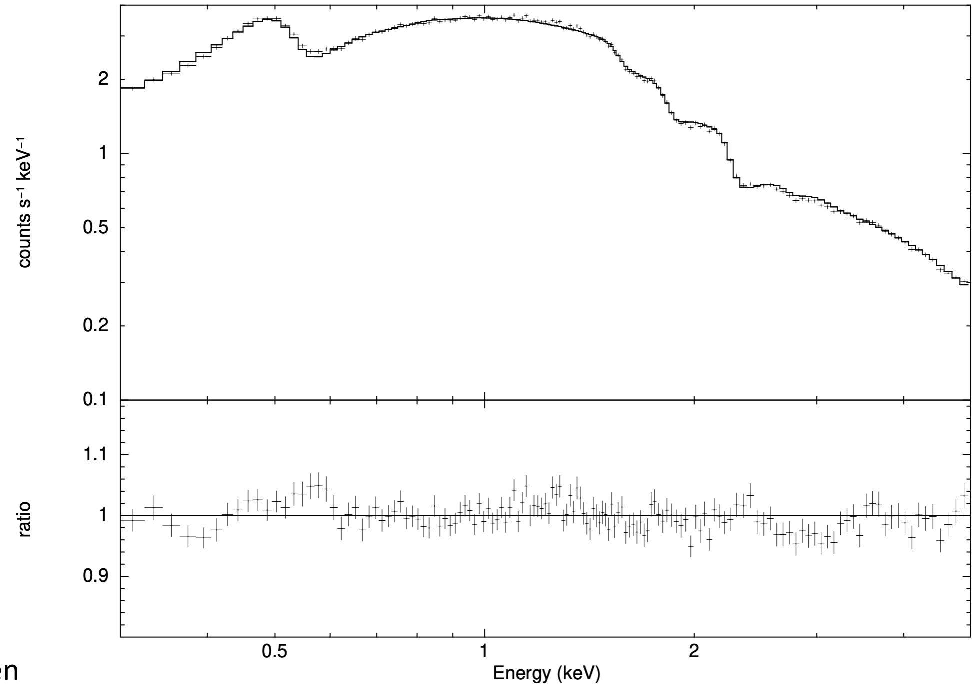
Contaminant model validated on several sources: 3C 273, RXJ1856-3754, 4XMM J111857.7+580323

Example:
MOS2 spectrum of 3C273 from revolution 3768 (~2020)
Model: double power-law (best fit to pn)

previous contaminant model



new contaminant model



S.Rosen

MOS contamination and redistribution

Redistribution:

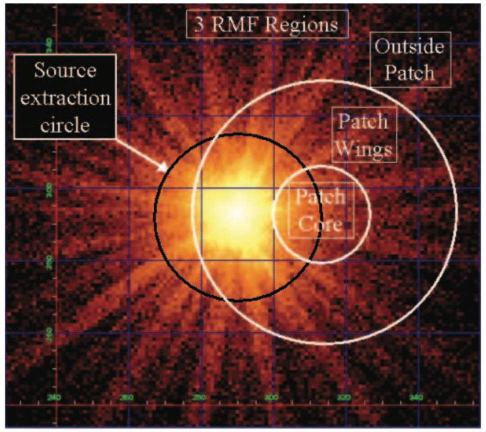
- Last significant update was in 2013

- New release is a substantial extension of the time-base: 5 new epochs of 300 revs each, from 2013 onwards

- Built upon the latest update of MOS time-dependent contamination

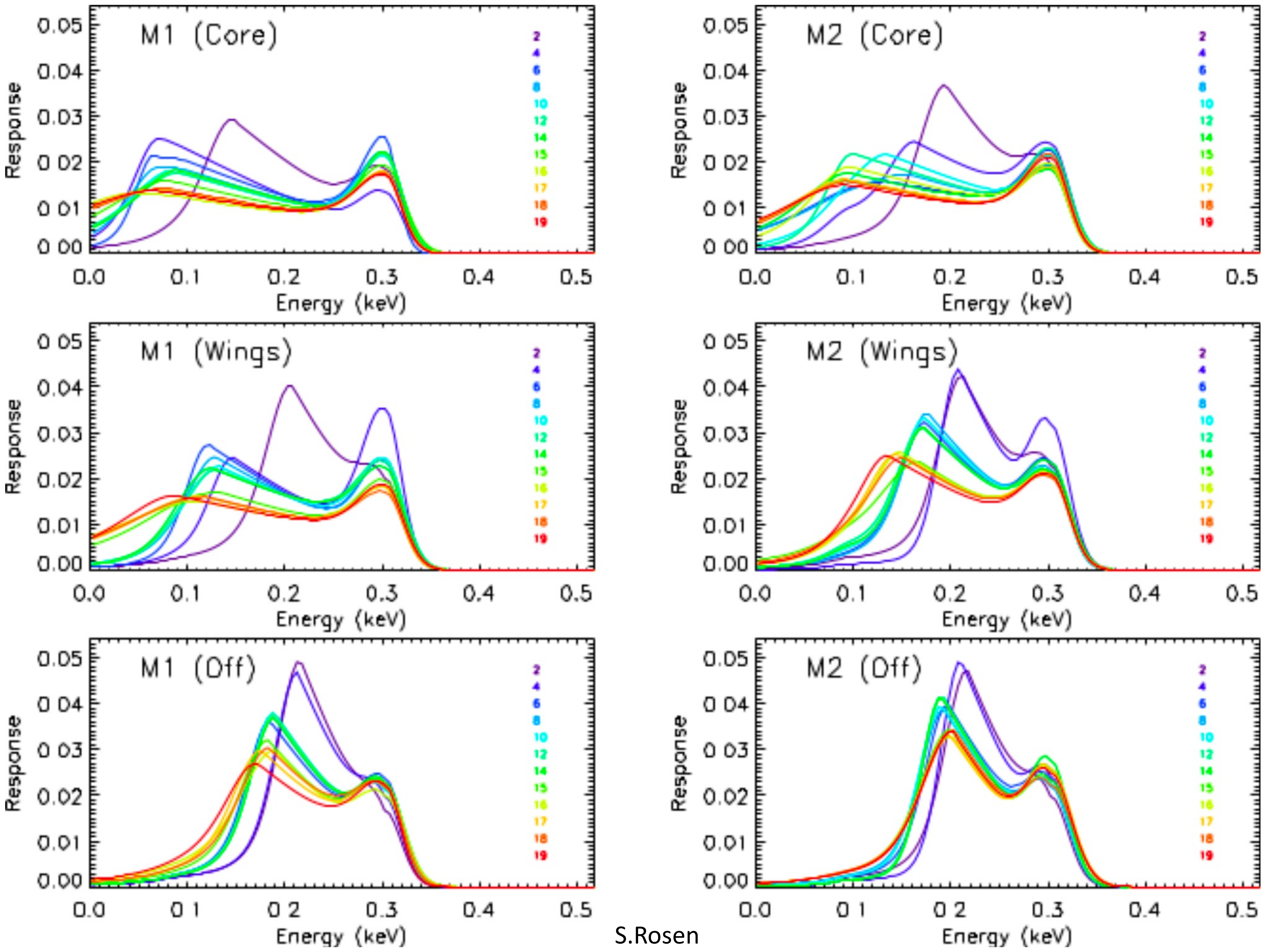
- Based on iterative adjustment of empirical RMF model, given data and assumed spectral models of
    - 1E 0102-7219
    - Zeta Puppis
    - RX J1856.5-3754

- Sources are observed on- and off-patch to allow
  RMFs to be produced for on-patch, patch wings and off-patch regions



MOS contamination and redistribution

Epochal evolution of redistribution functions @ 300 eV



Previous broad temporal behaviour continues

Especially for the core and wings regions:

- Drift to lower energies of the peak of the low-energy shoulder component
- Broadening of its low energy wing

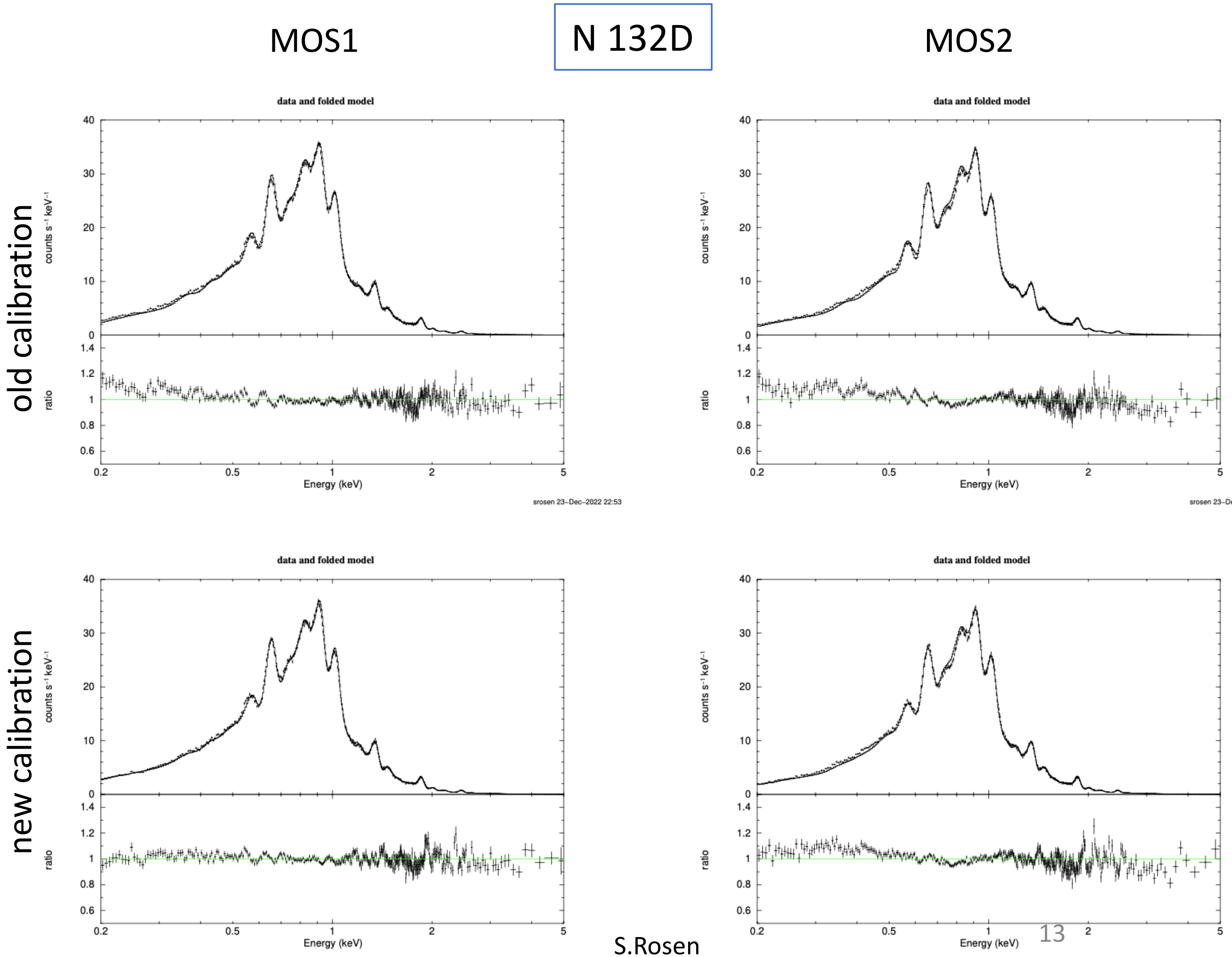
Colour coding represents different epochs

S.Rosen

MOS contamination and redistribution

Results tested on:

- RX J1856 and N 132D: spectral fits (using IACHEC models, free overall normalisation) show significant improvement in fit quality.
- RX J1856: temporal flux stability (in 0.2-0.5 keV band) is maintained.
- RX J0720.4-3125: (NS, observed in rev 3636) is a case showing worsening results – could be due to uncertainties in the model used.



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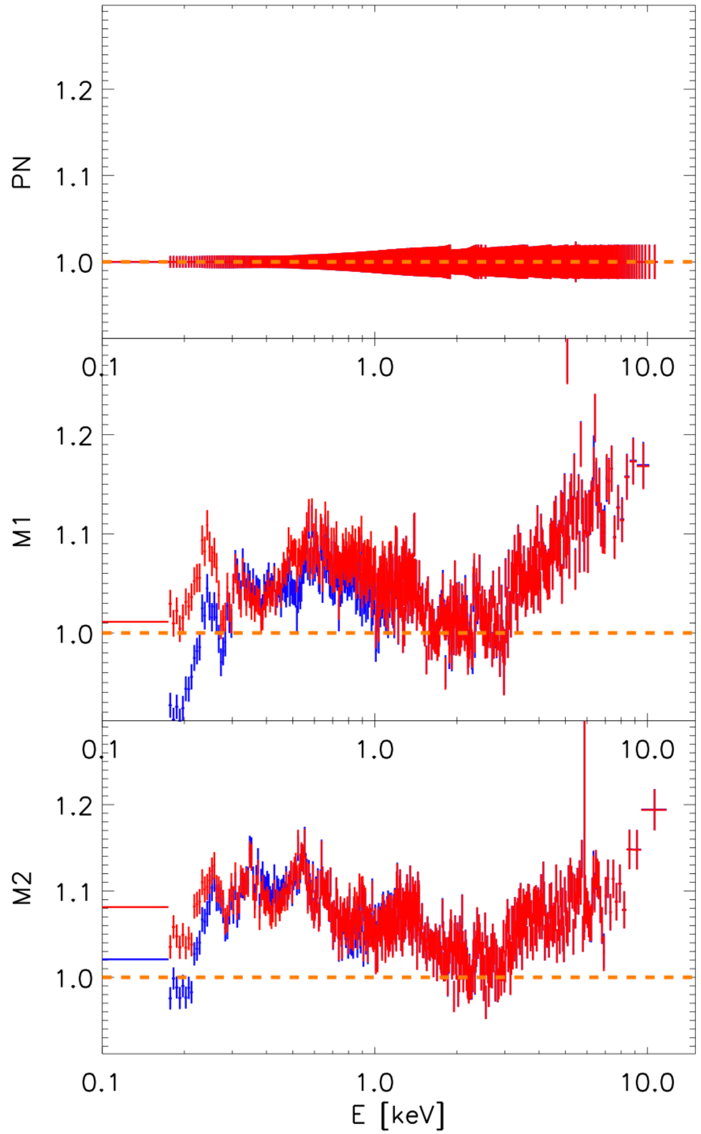
- Sample of 37 sources: stacked data/model ratios used to evaluate MOS-to-PN cross calibration; improved consistency between MOS1 and PN at lowest energies.

Stacked data/model, normalised to PN



Blue: old calibration

Red: new calibration

EPIC pattern fractions

Analysis indicates, unaccounted for differences between MOS spectra created with singles versus s+d+t+q

Affects data > 6 keV

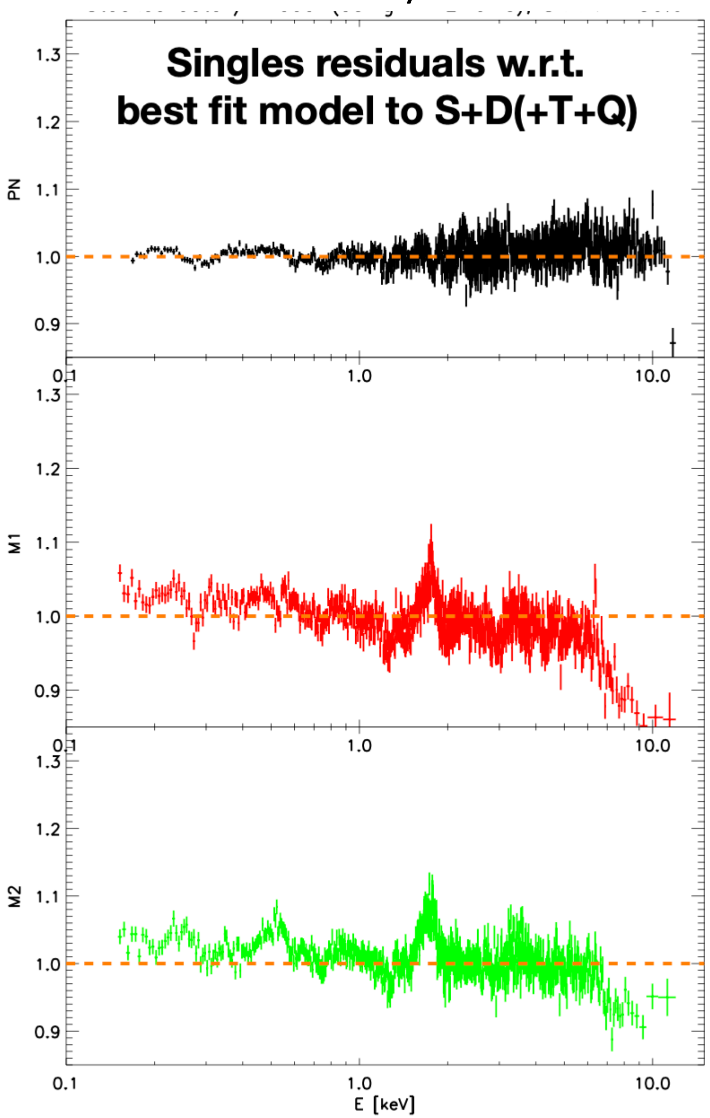
Assumed pattern fractions and respective QEs affect effective area

Discrepancies in pattern fractions may go some way to explaining the MOS-to-pn differences seen towards higher energy

Compare in-orbit data pattern fractions with calibration curves

Work ongoing…

Preliminary results



Off-axis flux calibration

Issues concerning off-axis flux calibration reported by:

- Mateos et al., A&A 496 (2009)
- Lusso, Astron. Nachr. 340, 4 (2019)

Analyses based on 2XMM / 3XMM EPIC flux comparisons:

show radial (and possible azimuthal) dependency of EPIC flux ratios

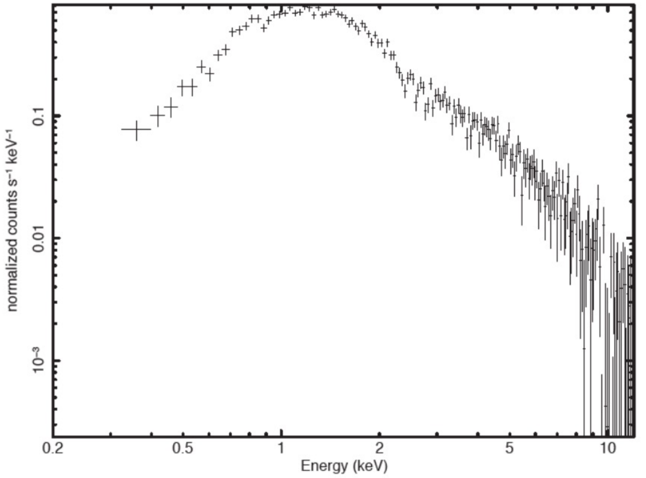
Results reproducible with 4XMM data, however interpretation not straightforward due to:

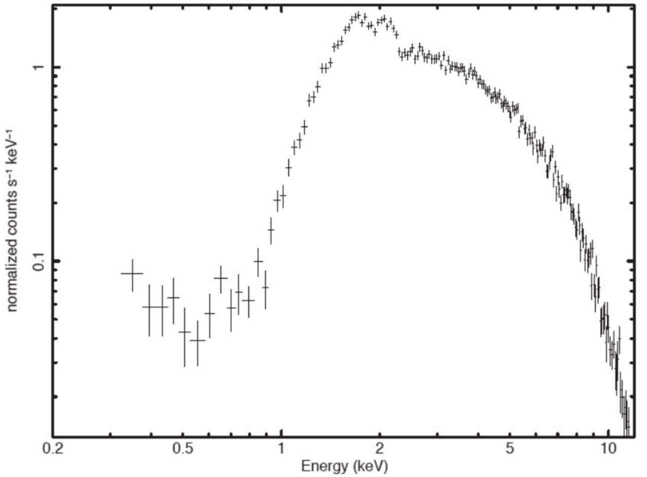
- Count rates – to – flux conversions
- Background
- Source variability

In order to investigate vignetting calibration:

investigate individual sources, e.g. raster observations (archival and new)

Off-axis flux calibration



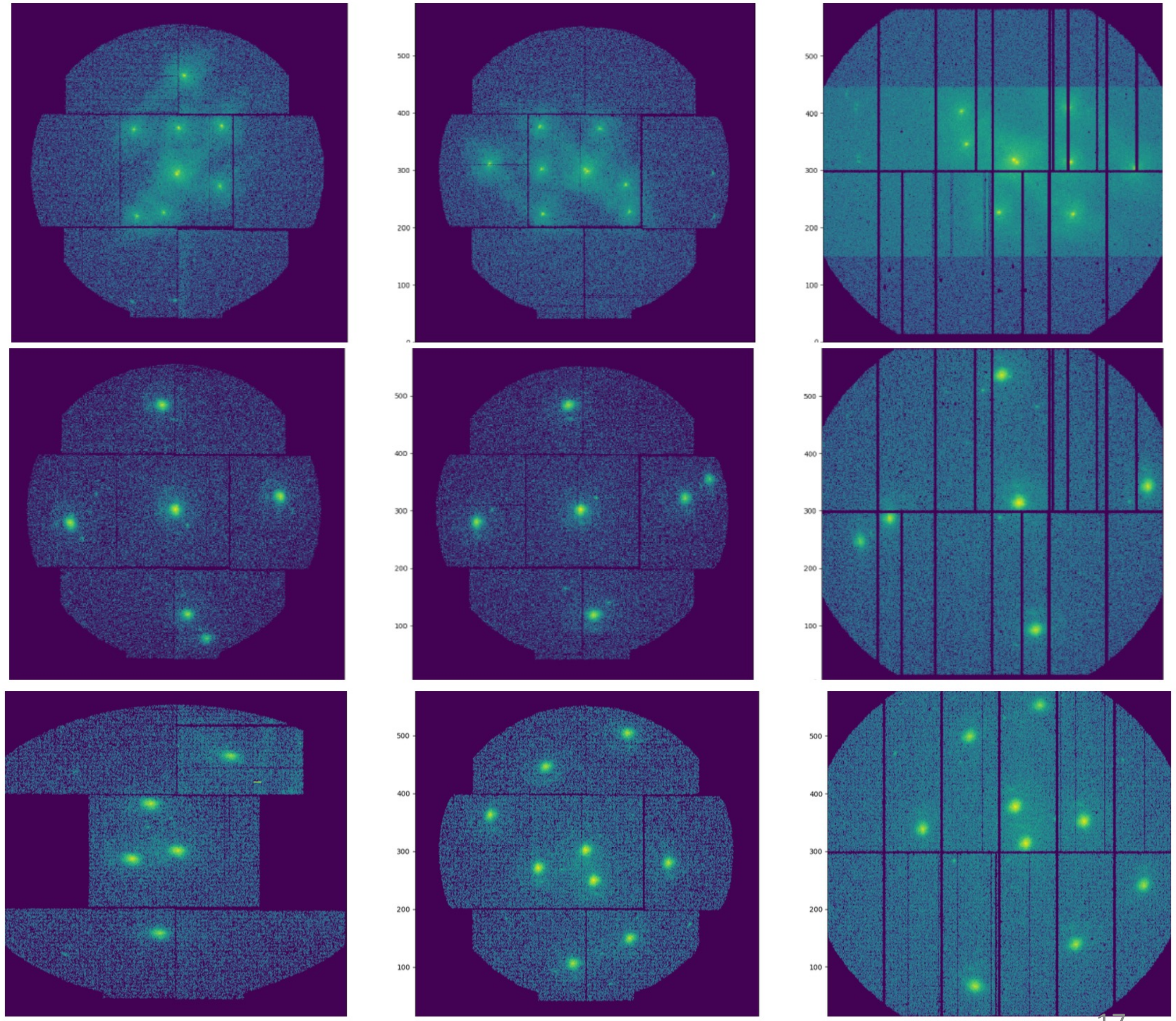


Raster scan observations (in DET coordinates)

SNR 3C58
(2000/2002)

SNR G21.5-09
(2000/2001)

SNR G21.5-09
(2021)



Off-axis flux calibration

PN:
- vignetting correction accurate to ~ ± 5%

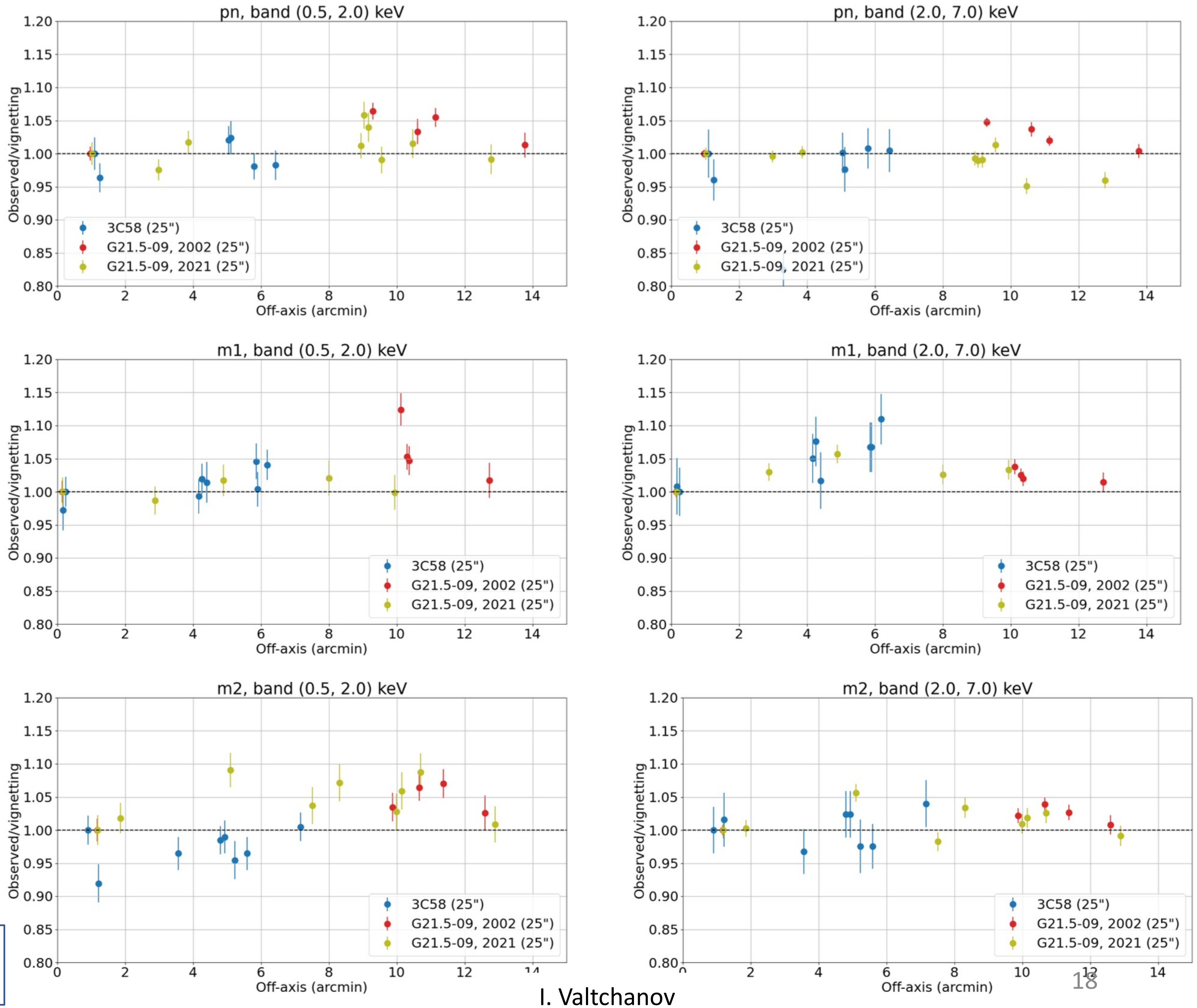
MOS1:
Low E band:
- vignetting correction within ~ 5%;
- results depend on choice of normalising obs

High E band:
- larger deviations at moderate radial distance (esp. 3C58)

MOS2:
- 3C58 and G21.5 consistency strongly dependent on choice of normalising observation (8% effect)

3C58 normalised to rev 47

Normalised vignetting corrected count rates



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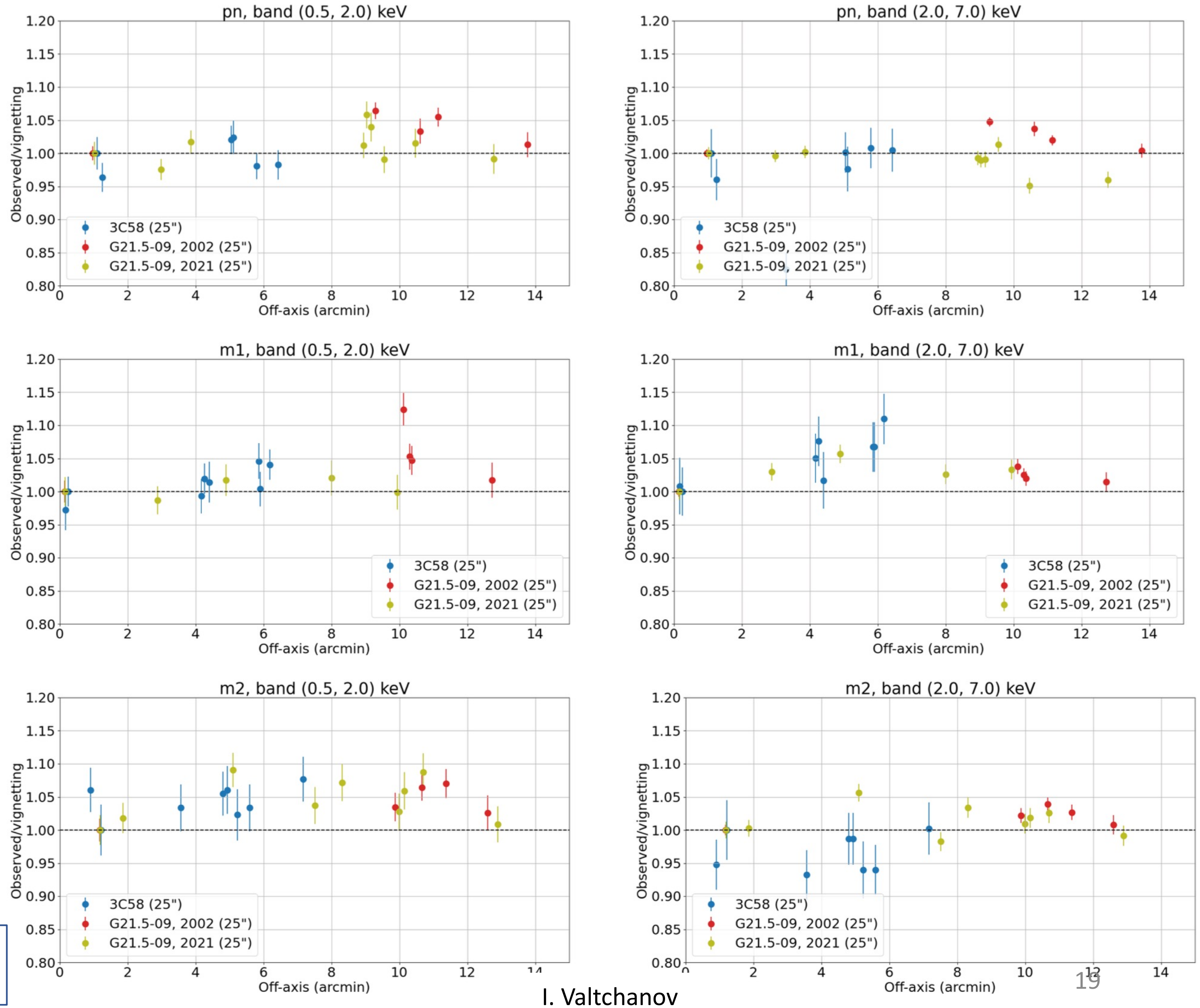
3C58 normalised to rev 506

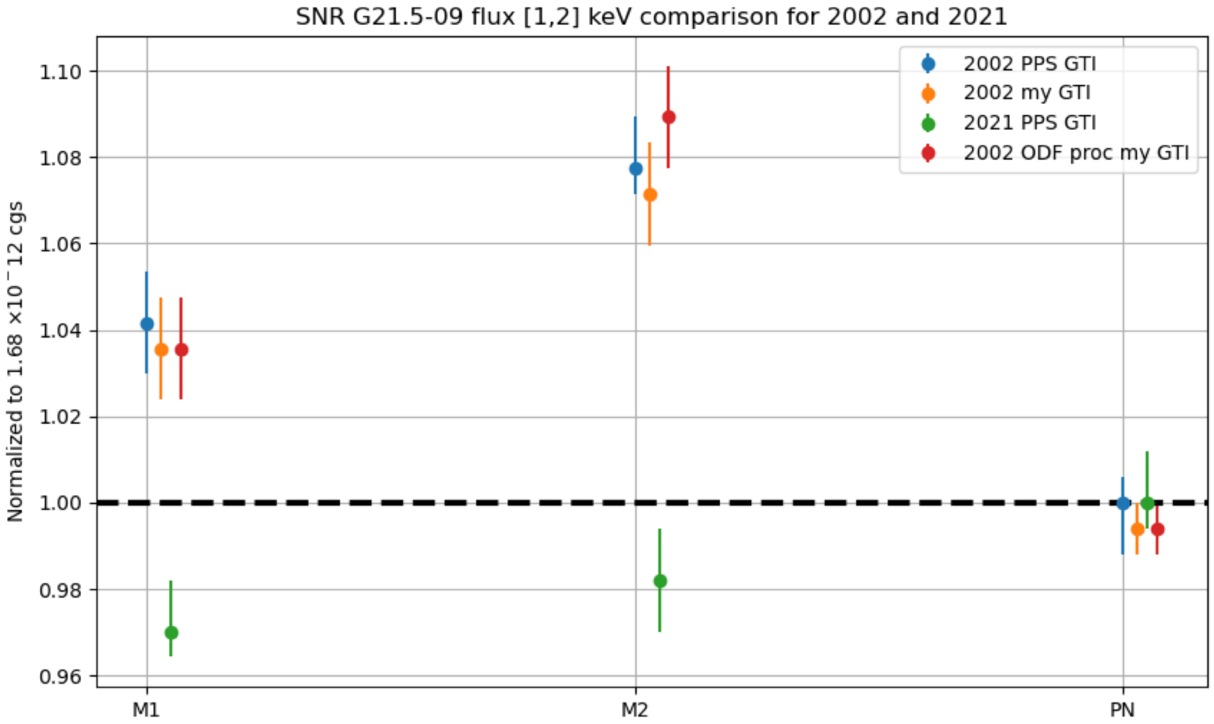


Off-axis flux calibration

Relative flux ratios for G21.5 for the boresight observations in 2002 and 2021:

~ 6% difference for MOS1

~ 10% difference for MOS2



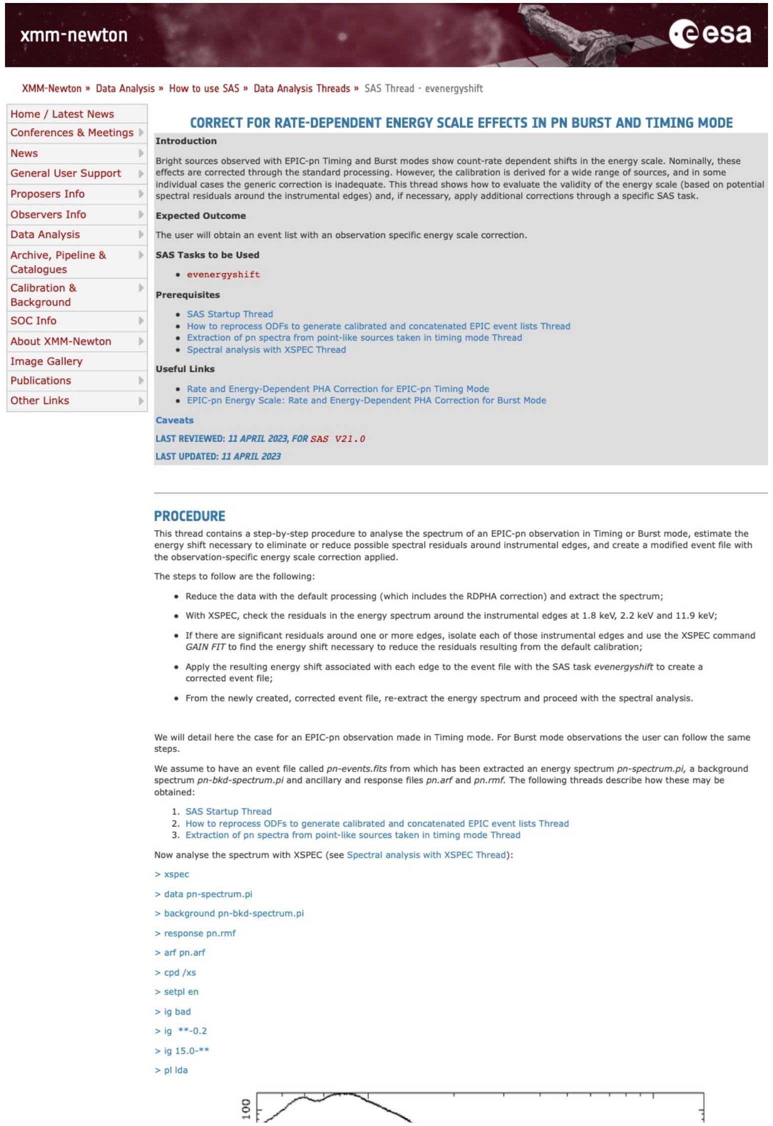
I. Valtchanov

Re-evaluate results given the new MOS response updates...

Analysis guide for observation specific RDPHA correction

- Bright sources observed with EPIC-pn Timing and Burst modes show count-rate dependent shifts in the energy scale.
- Nominally, these effects are corrected through the standard processing: RDPHA correction
- However, the calibration is derived for a wide range of sources
- In some individual cases the generic correction can now be refined:
  `evenergyshift` (SAS 21)
- The analysis thread describes how, for a particular observation:
  - to evaluate the validity of the energy scale
  - to apply additional corrections (if required)

✓ https://www.cosmos.esa.int/web/xmm-newton/sas-thread-evenergyshift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XMM-Newton » Data Analysis » How to use SAS » Data Analysis Threads » SAS Thread - evenergyshift

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CORRECT FOR RATE-DEPENDENT ENERGY SCALE EFFECTS IN PN BURST AND TIMING MODE

Introduction

Bright sources observed with EPIC-pn Timing and Burst modes show count-rate dependent shifts in the energy scale. Nominally, these effects are corrected through the standard processing. However, the calibration is derived for a wide range of sources, and in some individual cases the generic correction is inadequate. This thread shows how to evaluate the validity of the energy scale (based on potential spectral residuals around the instrumental edges) and, if necessary, apply additional corrections through a specific SAS task.

Expected Outcome

The user will obtain an event list with an observation specific energy scale correction.

SAS Tasks to be Used

- `evenergyshift`

Prerequisites

- SAS Startup Thread
- How to reprocess ODFs to generate calibrated and concatenated EPIC event lists Thread
- Extraction of pn spectra from point-like sources taken in timing mode Thread
- Spectral analysis with XSPEC Thread

Useful Links

- Rate and Energy-Dependent PHA Correction for EPIC-pn Timing Mode
- EPIC-pn Energy Scale: Rate and Energy-Dependent PHA Correction for Burst Mode

Caveats

LAST REVIEWED: *11 APRIL 2023*, FOR SAS V21.0

LAST UPDATED: *11 APRIL 2023*

PROCEDURE

This thread contains a step-by-step procedure to analyse the spectrum of an EPIC-pn observation in Timing or Burst mode, estimate the energy shift necessary to eliminate or reduce possible spectral residuals around instrumental edges, and create a modified event file with the observation-specific energy scale correction applied.

The steps to follow are the following:

- Reduce the data with the default processing (which includes the RDPHA correction) and extract the spectrum;
- With XSPEC, check the residuals in the energy spectrum around the instrumental edges at 1.8 keV, 2.2 keV and 11.9 keV;
- If there are significant residuals around one or more edges, isolate each of those instrumental edges and use the XSPEC command *GAIN FIT* to find the energy shift necessary to reduce the residuals resulting from the default calibration;
- Apply the resulting energy shift associated with each edge to the event file with the SAS task *evenergyshift* to create a corrected event file;
- From the newly created, corrected event file, re-extract the energy spectrum and proceed with the spectral analysis.

We will detail here the case for an EPIC-pn observation made in Timing mode. For Burst mode observations the user can follow the same steps.

We assume to have an event file called *pn-events.fits* from which has been extracted an energy spectrum *pn-spectrum.pi,* a background spectrum *pn-bkd-spectrum.pi* and ancillary and response files *pn.arf* and *pn.rmf.* The following threads describe how these may be obtained:

1. SAS Startup Thread
2. How to reprocess ODFs to generate calibrated and concatenated EPIC event lists Thread
3. Extraction of pn spectra from point-like sources taken in timing mode Thread

Now analyse the spectrum with XSPEC (see Spectral analysis with XSPEC Thread):

```
> xspec
> data pn-spectrum.pi
> background pn-bkd-spectrum.pi
> response pn.rmf
> arf pn.arf
> cpd /xs
> setpl en
> ig bad
> ig **-0.2
> ig 15.0-**
> pl lda
```

Column-by-column RDPHA correction

Conclusions from the investigation:

- Limited per-column data
- Nominally different rate-dependencies per column, with large uncertainties in fit parameters
- No significant improvement in RDPHA correction possible

See Technical Note (S. Migliari et al.):

✓ https://xmmweb.esac.esa.int/docs/documents/CAL-TN-0233-1-0.pdf

XMM-Newton Technical Note

XMM-SOC-CAL-TN-0233

On the Rate and Energy-Dependent PHA Correction for EPIC-pn Fast Modes: Column by Column Analysis

Simone Migliari and Michael Smith

25 May 2022

1 Introduction

In EPIC-PN fast mode observations, there is evidence for a rate-dependent shift in PHA-channels of the collected photons: above a certain threshold, the higher the total count-rate the larger the shift to higher PHA-channels. Furthermore, within a single observation, the higher the spectral energy-channel, the larger the shift. The assumed origin of the rate-dependent shift is a higher charge transfer efficiency due to an overall increase in shifted charge. Hence, rather than simply the count rate, the most useful parameter to describe the effect is the rate of shifted electrons.

In Migliari & Smith (2019) and Migliari et al. (2020), we analysed all the archive EPIC-PN fast mode observations available at the time to calibrate their energy shifts as a function of shifted electron rate. One of the key choices in the analysis was to calculate the rate and extract the spectra from an area of the CCD of 21 columns, centered on the brightest. From the selected area, for each observation, we extracted two parameters: 1) the number of shifted electrons of the CCD caused by the impinging photons, and 2) the energy peak of a Gaussian fit to a proxy of the reference line edges. This way, we could analyse a plot with rate of shifted electrons vs reference energy for each observation. Given that, in absence of a rate-dependent energy shifts, the reference energy should not vary, we calculated the observed discrepancy to a constant energy line and created CCFs to correct for it, given the shifted electron rate of the observation.

The current CCF files (EPN_CTI_0053.CCF and EPN_CTI_0054) correct a rate dependent effect in the EPIC-pn Timing and Burst Modes that affects the energy-scale precision, and are used by default since SAS 20. This rate-dependent correction, called RDPHA, is calculated in the PHA space (see Guainazzi et al. 2013, 2014). The RDPHA is a third correction to be applied for energy-scale accuracy of the EPIC-pn timing and burst modes, the other two being X-ray Loading and the special gain correction (Guainazzi et al. 2014).

In the analysis described above, we deliberately lose information on the specific columns and on their possible different responses. In this work, we repeat the analysis column by

Proton response matrices

”Design and characterisation of a prototype proton response matrix for the XMM-Newton mission” Fioretti et al. Proc. SPIE, V 11822, id. 118221F (2021)

- A proton response matrix would allow a better understanding of the proton radiation environment, with the aim of modelling the in-flight non X-ray background
- The intention is to make matrices available via a SAS task
- Awaiting the release of the matrices by the team responsible…

Other activities

- **PSF investigations**:

  Analysis of PN PSF using AGN observations in Large Window mode:

  ✓ LW mode gives access to full PSF (in one direction)

  ✓ Allows higher SNR before pile-up regime than e.g. FF mode

  Preliminary results:

  - Current PSF description underestimates core & overestimates EE in wings (from a few 10” to 200”)
  - Implications for pn / NuSTAR:

    Could account for some of the discrepant 3-7 keV flux as originally reported for 3C 273

  Complicated analysis, further investigation required…

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- **MOS time-dependent energy scale calibration**:
  - Based on exposures illuminated by on-board Fe55 source
  - Source has become too faint to directly measure main components: serial CTI, parallel CT and gain
  - New method put in place, a compromise solution deriving parallel CTI from CCD averaged data
  - Can perhaps be refined to allow more accurate solution

EPIC calibration recommendations from the 2022 UG

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• **2021-06-10/09:** The UG recommends to finalize the analysis of the possibility of a column by column rate-dependent PHA correction of pn in Burst and Timing modes and publish the conclusions.	Done
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• **2022-05-17/06:** The UG recommends to verify the pattern fractions determined from in-orbit data with the expected pattern fractions	Ongoing
• **2022-05-17/07:** The UG recommends the creation of proton response matrices and to make them available through SAS	Ongoing