Description of the work flow

The provided software in intended to help a general user to implement the results of the study of the XMM-Newton/EPIC effective area cross-calibration bias (Nevalainen & Molendi, 2023) into spectral analysis of the XMM-Newton/EPIC data. The user has the possibility to estimate the effect of the systematic uncertainties due to the cross-calibration bias and its scatter on the model parameters. The implemented cross-calibration information is valid in the 0.5-6.1 keV band. The procedures implemented in the software and their role in the work flow are described in detail below.

1) The work flow begins with the usual fitting of the X-ray spectrum with the standard SAS-produced auxiliary response file (arf-file). If the data being analysed are obtained with the pn instrument, the current implementation allows the user to choose whether to estimate the effect of the cross-calibration bias between pn and MOS1 or between pn and MOS2. If the user wishes to analyse the data obtained with MOS1 or MOS2, the procedure allows the evaluation of the effect of the cross-calibration bias between that instrument and the pn instrument.

2) Using the statistical results for the measure of the cross-calibration in the cluster sample corresponding to the choice of the instrument pair made in step 1 the software draws a random cross-calibration bias data curve.

3) The data set obtained in step 2 is fitted with a 4th order polynomial.

4) Depending on the choice of the instrument pair made in step 1, the effective area column in the standard SAS-produced arf-file used in the beginning of the analysis is multiplied or divided by the best-fit 4th order polynomial obtained in step 3. If, for example, the user wants to estimate the effect of the MOS1/pn cross-calibration bias on the spectral analysis of the MOS1 (pn) data, the 4th order polynomial obtained in step 3 by fitting the randomised MOS1/pn cross-calibration bias data should be used to multiply (divide) the standard MOS1 effective area.

5) Steps 2-4 are repeated by a large number of times in order to produce a statistically meaningful sample of modified arf-files.

6) The spectral fit of step 1 is repeated, replacing each time the original arf-file with one of the arf-files generated by the above procedure.

7) The distribution of the best-fit parameters obtained with the modified arf-files can be analysed in order to evaluate the systematic uncertainty related to the cross-calibration bias.

Instructions for using the software

The run is controlled by modifying the parameters in the **input.par** file. The software is run in two steps. First, the randomised cross-calibration bias curves are created with IDL program **crosscal.pro**. Second, the information is used to create new arf-files using FTOOLS package which is controlled by a C shell wrapper script **write_arfs**.

1) input.par

The software reads the necessary parameters from the **input.par** file. The contents of the **input.par**-file are described below.

1.line: The input instrument whose arf-file is being modified. The options are 'pn', 'm1' and 'm2'.
m1 (m2) means MOS1 (MOS2)

2. line: The name of the input arf-file being processed with the software. The software distribution includes example arf-files **m1.arf**, **m2.arf** and **pn.arf** which can be used to test the code.

3. line: The instrument pair to be used. The options are 'm1pn', 'm2pn', 'pnm1' and 'pnm2'.
The first two chracters refer to the instrument whose spectrum is being analysed and whose arf-file is being modified. It must correspond to the input arf-file. The last two characters refer to the second instrument of the pair whose cross-calibration information is used.

4. line: The number of the modified arf-files to be generated

2) crosscal.pro

The IDL program **crosscal.pro** uses the cross-calibration information from Nevalainen & Molendi (2023) to compute the XMM-Newton/EPIC cross-calibration bias values for each photon energy in the user-input arf-file. The randomisation simulates the measured scatter of the cross-calibration bias. For each randomisation loop the program stores the cross-calibration bias values into a separate ascii file with name *crosscal*.txt. The full file names reflect the loop number and the user's choices on the input instrument and the cross-calibration instrument pair to be used (see below).

The program is executed in IDL by entering **.r crosscal** in the command line. The program produces plots of the results in eps-format whose parameters can be chanced to match the data at hand.

3) write_arfs

The linux C shell script **write_arfs** reads the *crosscal*.txt files containing the cross-calibration bias curves obtained by running the crosscal.pro as explained above. The script computes the new effective areas which are stored as 'SPECRESP' columns in the new arf-files produced by the script. The names of the produced arf-files are otherwise identical to those of the files produced by the crosscal.pro program above, except that the ending **.txt** is replaced with **.arf**.

The script works under csh and tcsh. You can check which shell you are currently using by entering **ps -p $$** and, if necessary, to activate C shell by entering **csh** or **tcsh.** You need to have FTOOLS installed and activated. The script is executed by entering **source write_arfs** in the command line.

Testing

Test 1:

We tested the above procedures by generating modified cross-calibration bias curves for MOS1/pn and MOS2/pn pairs. Using the distribution of the values at each energy we computed the sample median and the standard deviation. We found that using 1000 realisations, the median of the randomised sample agrees with that of the cluster data sample within 2% and the scatter, as measured by the standard deviation, is very similar in the two cases (see **Fig. 1**).

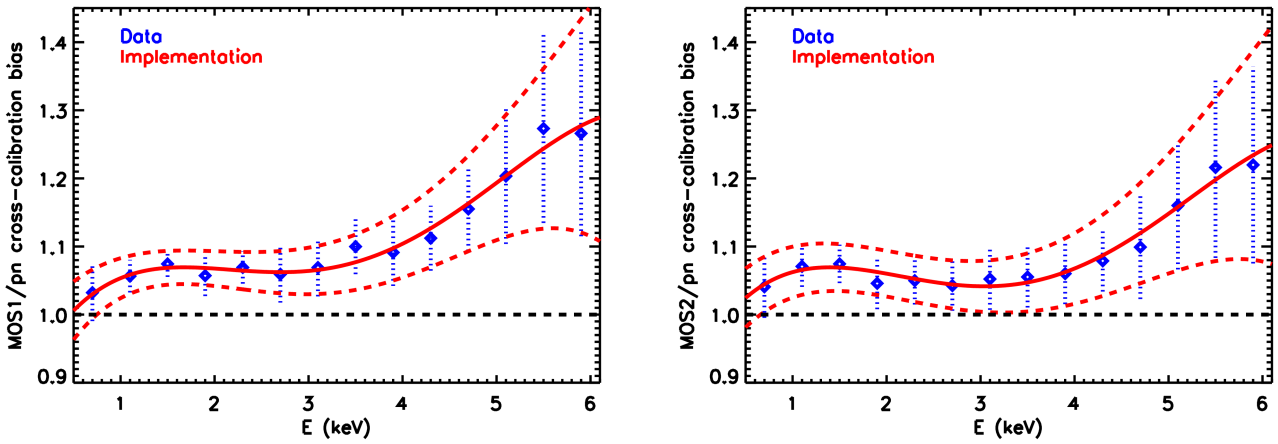

Fig. 1: The median (solid red line) and the variation as measured by the standard deviation (dashed red lines) of the cross-calibration bias obtained by the procedure laid out in the text using 1000 realisations. The blue symbols indicate the corresponding values obtained from the cluster data (Nevalainen & Molendi, 2003). The results for the MOS1/pn and MOS2/pn pairs are shown in the left and right panels, respectively. The horizontal dashed line indicates the expectation (unity) in case of no cross-calibration bias.

Test 2:

We then applied the corrections to XMM-Newton/EPIC spectral data of A1795. We started the analysis by fitting the 0.5-6.1 keV band with a single temperature *mekal* model absorbed by *phabs* model. The best-fit values alone are not very meaningful since the spectrum is extracted from a circular region of 6 arcmin (~0.4 Mpc) radius around the cluster center and thus contains many temperature phases. The rationale for fitting the data with a single-temperature model is to quantify approximately the systematic effect on the cluster temperature considering the effective area cross-calibration bias.

For each observational spectrum we created 1000 modified arf-files using the above tools and re-fitted the data. Assuming for the sake of the argument that the calibration of the pn effective area is very accurate (i.e. modifying the MOS arf-files) the distributions of the best-fit temperatures (upper panels in **Fig. 2**) peak at lower temperatures than those obtained when modifying the pn arf-files (lower panels in **Fig. 2**). Under the above assumption the software renders the MOS effective areas harder which results in softer best-fit models. Thus, the tool works as expected. The systematic chance in the temperature is ~10% when considering the MOS/pn cross-calibration bias for this particular cluster and region. The scatter is at a few % level.

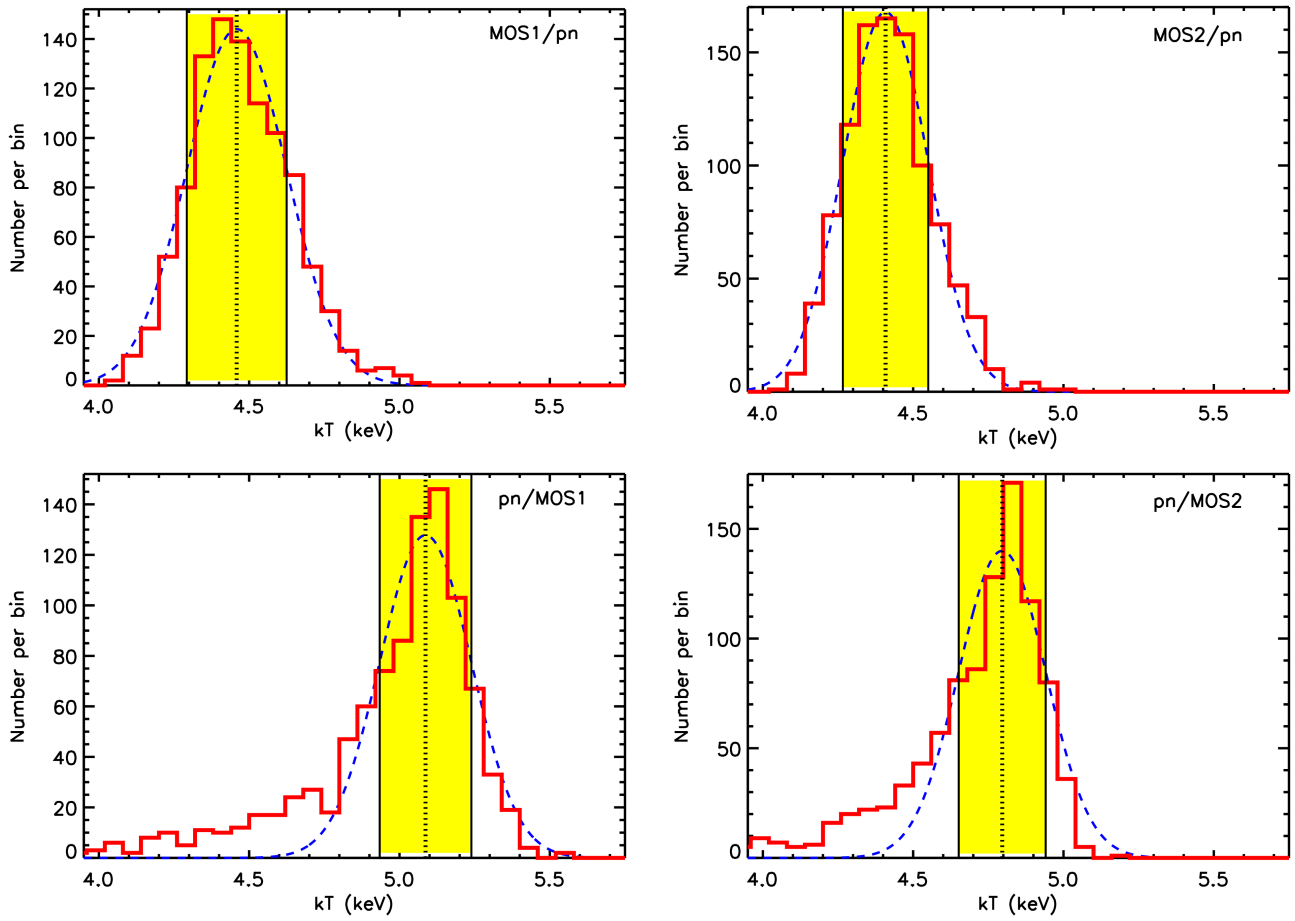

Fig. 2: The distributions of the best-fit values for the temperature of A1795 galaxy cluster as obtained from the spectral fits to the 0.5-6.1 keV band of MOS1 (upper left), MOS2 (upper right) and pn data (lower panels) are shown with the red histograms. For each fit, the standard SAS-produced arf-file was replaced by one modified according to the cross-calibration information reported in Nevalainen & Molendi (2023) for the instrument pair indicated in the top right corner of each panels. The best-fit Gaussians to the above distributions are shown as a blue dashed line. The best-fit centroid of the Gaussian and the central interval containing 68% of the probability interval are indicated with a black dashed line and the yellow band, respectively.