Multi-Parameter Gain Drift Correction Of X-Ray Micro-Calorimeters For the X-Ray Integral Field Unit

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Abstract: With its array of 3840 Transition Edge Sensors (TESs), the X-Ray Integral Field Unit (X-IFU) onboard Athena (launch in 2028) will provide spatially resolved high-resolution spectroscopy (2.5eV FWHM up to 7keV) from 0.2 to 12keV, with an absolute energy scale accuracy of 0.4eV. Slight changes in the TES operating environment can cause significant variations in its energy response function, which may result in systematic errors in the absolute energy scale. We plan to monitor such changes via onboard X-ray calibration sources and correct the energy scale accordingly using a linear or quadratic interpolation of gain curves obtained during ground calibration. However, this may not be sufficient to meet the 0.4eV accuracy required for the X-IFU. Therefore, we investigated a new two-parameter gain correction technique, based on both the pulse-height estimate of a calibration line and the baseline value of the pixels. From simulated energy scale functions, we show that this technique can accurately correct gain drifts over the instrument bandpass despite significant deviations in heat sink temperature, bias voltage, thermal radiation loading and linear amplifier gain. We also address potential optimisations of the onboard calibration source and compare the performance of this new technique with those previously used.

1. The Energy Scale Function

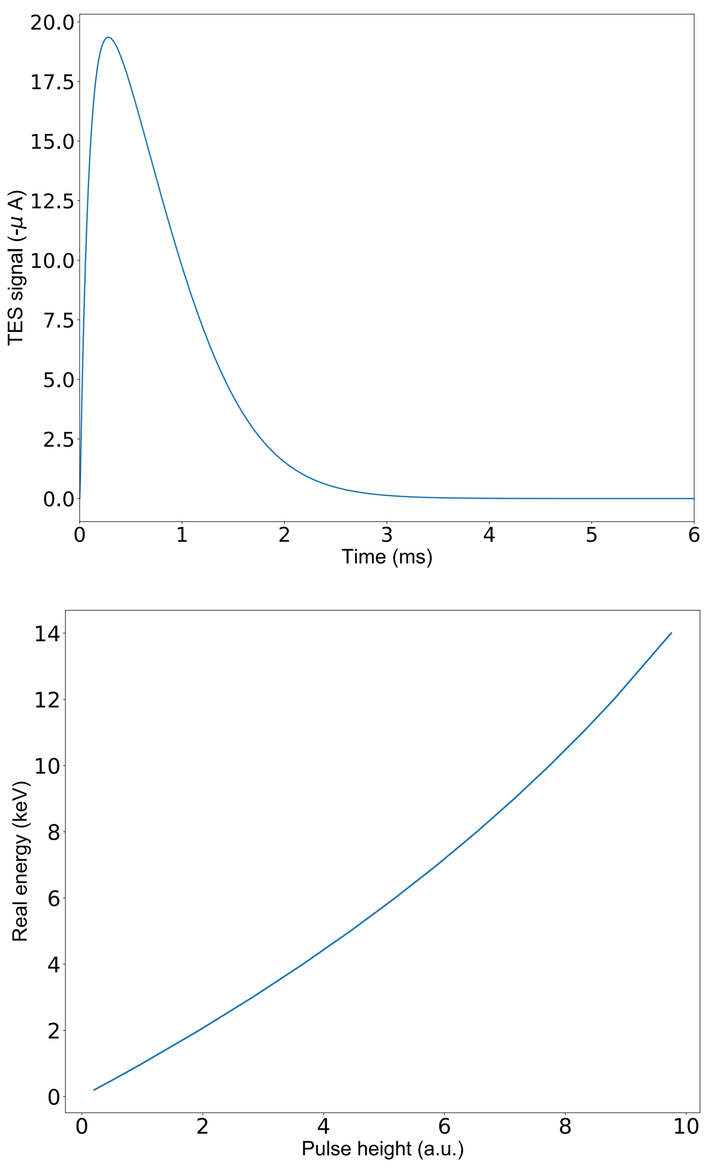

Figure 1: *(Top)* Baseline-subtracted pulse (μA) of a 1 keV impact photon simulated with *tessim* [5] as a function of time. *(Bottom)* Simulated energy scale function of a X-IFU TES at electrothermal equilibrium.

- The X-IFU [1] will have an array of **3840 AC-biased superconducting Transition Edge Sensors (TESs)** [2] read out using frequency domain multiplexing [3,4].
- An X-ray photon increases the TES temperature and in turn its resistance (calorimetric detection). As TESs are voltage biased, this creates **a current pulse** *(Fig. 1)*. This pulse is filtered [5] to find its **pulse-height estimate (PHA)**.
- ***Energy scale*** *(or gain) function:* link between the **pulse height estimate** (a.u.) and the **photon energy** (in keV). Initially measured **on the ground, non linear** *(Fig. 1)*.
- Small drifts in TES operating conditions can cause large drifts in the energy scale function ⇨ significant systematic errors in knowledge of the energy scale!
- The energy scale is **monitored in-flight** using an **onboard Modulated X-Ray Source** (MXS).

0.4eV (FWHM) absolute calibration requirement of the energy scale over 0.2-7 keV

⇩

Energy scale correction!

2. Correcting Drifts In the Energy Scale Function

- *Method:* Energy scale functions and the referential line(s) are **simulated** via the X-IFU's End-To-End simulator **SIXTE** (*tessim* function [6]).
- Gain functions are created for drifts in bath temperature (T_{bath}), bias voltage (V_{bias}), linear amplifier gain (L_{amp}) and thermal optical loading (P_{load}) ⇨ **comparing the accuracy of different correction techniques**.
- *Linear stretch:* simplest correction. Homothetic transformation using the calibration line.
- *Non-linear correction (Fig. 2) [7]:* **drift ≡ effective temperature**. The new gain curve is interpolated using 3 gain functions and the effective temperature.

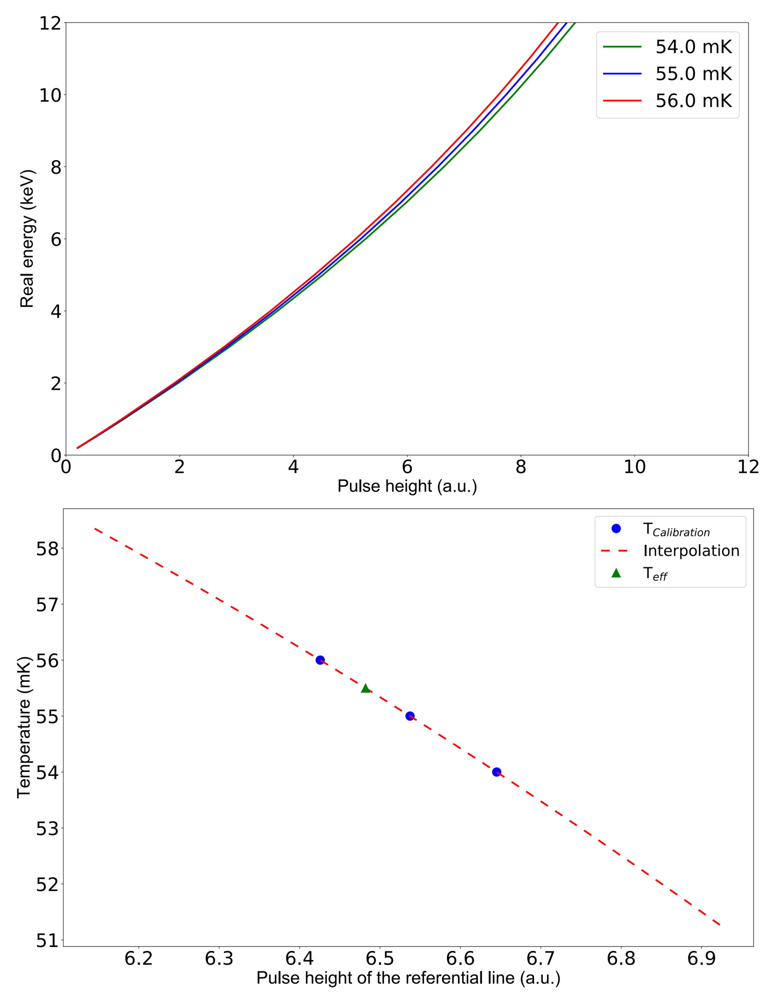

Figure 2: Principle of the non-linear drift correction [7] *(Top)* Three energy scale functions for different temperatures used for the correction *(Bottom)* Finding the effective temperature of the perturbation

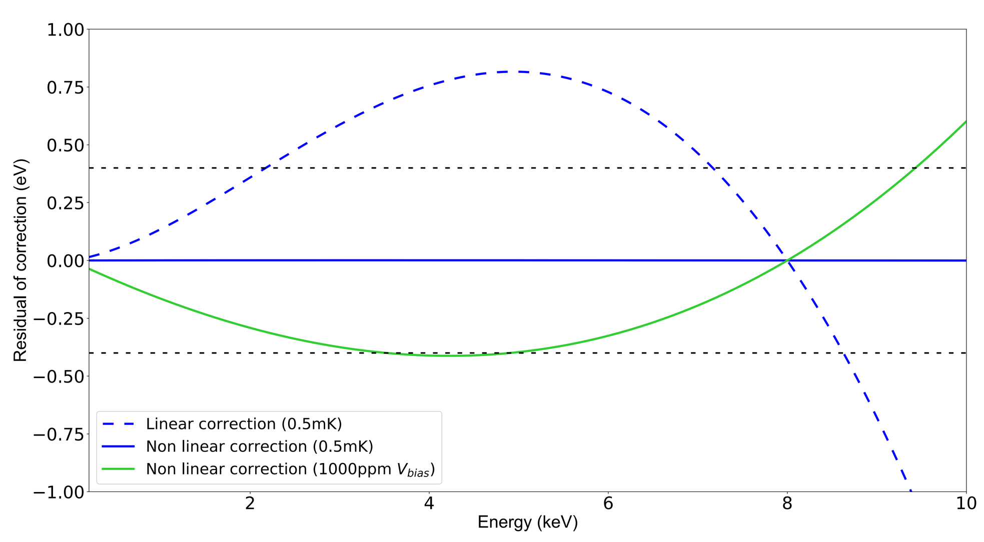

Figure 3: Residuals on the energy band for a 0.5mK bath temperature drift corrected with the linear and non-linear technique (blue dashed and full line) and a 1000ppm bias voltage drift corrected with the non linear technique (green). Dashed lines give the 0.4eV requirement.

Techniques:

- ✗ Linear correction
- ✓ Non linear correction

⇩

Can these techniques be improved?

Gain drift correction is possible using a referential calibration line. A linear correction is not enough (intrinsically non-linear drifts). Non-linear correction is accurate, but not sufficient in some cases.

3. Multi-Parameter Correction

- **Two parameters are available** on a pulse: **its pulse height estimate and the pixel baseline.** Transposing the idea of the **non linear technique into a two-parameter space.**
- *Method:* a set of six calibration gain functions for two different parameters (here {T_{bath}, L_{amp}}) is used to find **two effective parameters** (inverse problem):

$$f(T_{bath}, L_{amp}) = (PHA_{ref}, Ba_{ref})$$

$$(T_{bath,eff}, L_{amp,eff}) = min_{T_{bath},L_{amp}}(||(PHA_{flight}, Ba_{flight}) - f(T_{bath}, L_{amp})||_2)$$

- **Two-dimensional quadratic interpolation** of the new energy scale function using the two-dimensional surface created by the calibration curves.
- The technique can be further improved by using two calibration lines (e.g. Cr+Cu Kα) *(Fig. 4)*.

	Non-linear correction	Multi-parameter correction (T_{bath}, V_{bias})	Multi-parameter correction (T_{bath}, L_{amp})	Multi-parameter correction (2 lines)
T_{bath} (mK)	±3	±4	±4	±6
V_{bias} (nV_{rms})	±0.06	±2.5	±0.07	±4
L_{amp} (%)	±0.75	±0.08	±1.8	±2.0
P_{load} (fW)	+200	+500	+400	+500

Table 1: Maximal drift in considered parameters with respect to the TES equilibrium set point (T_{bath}=55mK, V_{bias}=51.6nV_{rms}, L_{amp}=0ppm, P_{load}=0fW) corrected within 0.4eV on [0.2-7] keV by the various correction techniques.

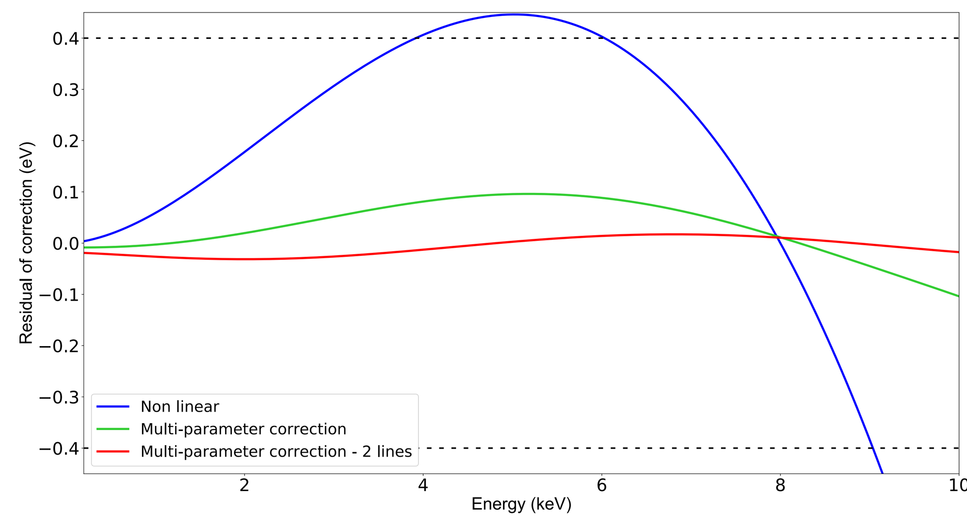

Figure 4: Residuals on the energy band for a 1% linear amplifier gain drift corrected with the non-linear (blue) and multi-parameter gain drift correction technique with one (Cu - red) or two calibration lines (Cr/Cu - purple). Dashed lines give the 0.4eV requirement.

Multi-parameter correction:

- ✓ Additional calibration curves (6 instead of 3) + baseline needed
- ✓ Operations during post-processing
- ✓ Standard non-linear correction remains possible
- ✓ Choice of the effective parameters to minimise the residuals

The multi-parameter technique uses the pulse height estimate of the pulse and the baseline of the pixel. It achieves accurate results (<0.4eV) for large drifts but remains to be tested on real-life TESs. Multiple improvements are possible by changing the effective parameters or by considering additional calibration lines.

4. The Influence of Statistics

- **Addition of a line = more accurate correction if lines are known perfectly...**
- ...but lines are not known perfectly! **Total MXS count rate: ~2-3 cts/s/pix** (TBC).
- Assessing the effect of statistics on the correction residuals. ⚠ Different from the statistical error on the line itself!
- *Method:* Random Poissonian draws of photons in the line(s) [8] and fit using Cash statistics [9] in PHA space. Fitted PHA and baseline information used in the multi-parameter algorithm.
- Constraining the 'non-linear' part of the gain curves provides a more robust reconstruction ⇨ **high-energy lines.**
- For small drifts, a single line offers accurate results *(Fig. 5 - Left)*. For more complex drifts, a second line is needed to achieve lower residuals over the bandpass *(Fig. 5 - Right)*.

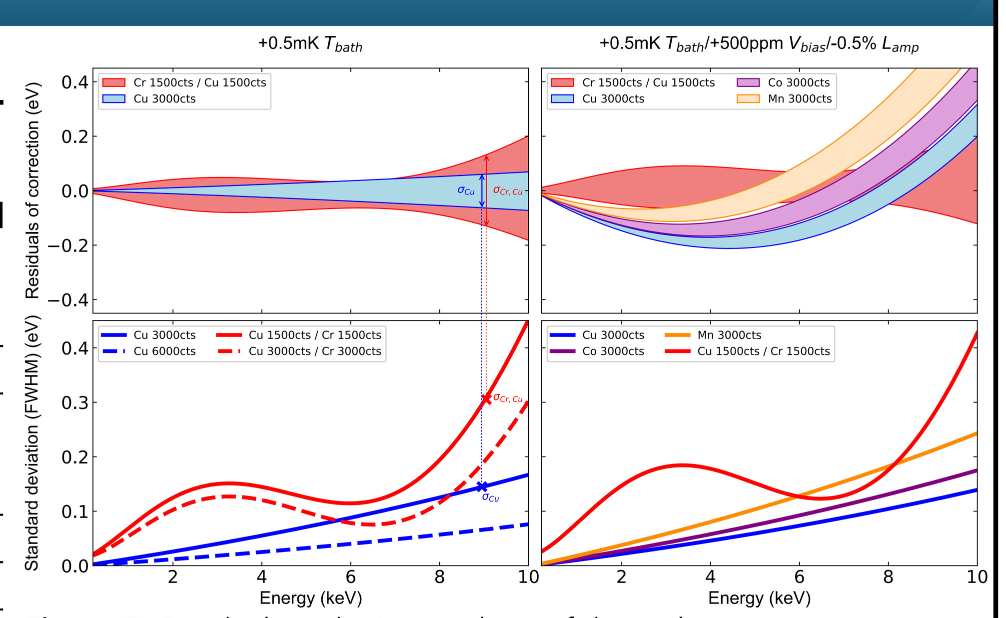

Figure 5: Residuals and ±1σ envelope of the multi-parameter correction of a +0.5mK T_{bath} drift *(Upper left)* and the standard deviation of the correction (FWHM) over the bandpass for different MXS configurations and count rates *(Lower left)*. Likewise for a 'complex' +0.5mK T_{bath}/500ppm V_{bias}/-0.5% L_{amp} drift *(Upper right)* along with the corresponding residuals *(Lower right)* for different MXS configurations and counts in the Kα line(s).

Statistics:

- ✓ Correction is degraded by statistics
- ✓ **Two lines not necessarily optimal**
- ✓ High-energy lines improve the robustness of the correction wrt statistics
- ? Tuneable configuration of the MXS?

A two-line correction is not always optimal when statistics are included. For a low number of counts and small drifts, a single line offers more accurate results. High energy lines (e.g. Cu, Co) give tighter constraints on the non-linearity of the gain curves, making the correction more robust to statistical errors over the bandpass.

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