Ancient TL

Short Communication

A note on count linearity in luminescence measurements using PMT modules

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Abstract

Deviations from anticipated instrumental readings in luminescence measurements can result in systematic uncertainties that are challenging to quantify. In this study, we address the issue of count rate linearity of photomultiplier modules commonly employed in luminescence readers. Considering instrumental thresholds and typical signal outputs, in most scenarios, this deviation is not a concern. However, in corner cases where detectors are operated in regions where non-linearity of count rates becomes significant, corrections are necessary. This is a well-known issue, but to the best of our knowledge, not all measurement systems utilise a correction. In this note, we provide some technical background and show that the impact on the equivalent dose can reach easily 2 % even in conservative scenarios. We then demonstrate how this can be post-corrected using a straightforward dead-time non-linearity correction implemented in the R package 'Luminescence'.

Keywords: Luminescence, Signal detection, Dead-time linearity correction, Systematic uncertainty

1. Introduction

Shortly after Dirk started his PhD in Heidelberg, we engaged in a discussion over managing light output to avoid the photomultiplier tube (PMT) operating within its non-linear response range. The cardinal rule tells us, as it is with every technical component, that it should be operated well within specified performance limits. In our case, the PMT had documented linear response characteristics up to 6×10^6 cts s^{-1} but was cut-off by the reader at 3.5×10^6 cts s^{-1}. This appeared to be a pretty conservative safety margin, still, should we be worried? In the PMT datasheet, we found *count linearity* defined as the value at which *"[. . .] 10 % count loss"* is still acceptable (Hamamatsu, 2008b). Luminescence dating practitioners may not call it linear if those very count values are used for equivalent dose (D_e) calculation.

Dirk then pointed out that count value underestimation can easily reach $\sim 2\%$ in case of $\sim 100,000$ counts per channel, for a resolution of 0.1 s per channel (e.g. 1×10^6 cts s^{-1}). Although such a count rate is likely perceived as a sufficiently bright signal by most practitioners, not causing sleepless nights, the difference did not seem negligible enough to be discarded. Hence, we used the correction formula already implemented in the R (R Core Team, 2025) package 'OSLdecomposition' (Mittelstraß et al., 2022) and simulated corrected PMT response for counting modules typically encountered in our luminescence readers. The results (Fig. 1) and their potential implications for luminescence measurements got our attention.

The count value underestimation reaches 7.5 % at a count-rate of 1×10^6 cts s^{-1} for the Hamamatsu H7421-50, which is usually preferred for infrared-radiofluorescence (IR-RF) measurements. Even the UV-blue sensitive PMTs commonly used for OSL and TL dating exhibit a 1.8 % and 2.6 % underestimation at the same count-rate. Of course, PMT signal dead-time correction is not a new issue. For instance, the Risø OSL/TL reader manual dedicates an entire chapter to it and describes a correction procedure (see Ch. 5 in Risø DTU, 2021). In the BINX-file, the logical parameter DTENABLED would indicate whether a correction was used.

However, how does non-linearity of counts translate, if this were to be the aim of a measurement, to an equivalent dose (D_e)? Should we correct the signals or does the correc-
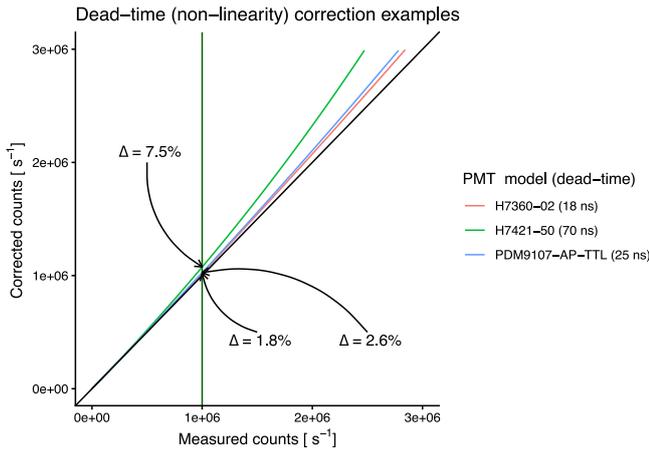
Figure 1: Examples for dead-time non-linearity corrected photon counts of different PMT models commonly installed in the luminescence readers. The cut-off shown by the vertical line was chosen arbitrarily to provide a reference for comparison. The Δ values show the expected deviation between measured and corrected value at the reference level.

tion introduce additional problems?

These questions are quite general and part of ongoing endeavours in our community to determine the origin, magnitude, and statistical significance of all kinds of measurement uncertainties (e.g., Galbraith, 2002; Duller, 2007; Li, 2007; Adamiec et al., 2012; Kreutzer et al., 2013; Zink, 2015; Bluszcz et al., 2015; Carter et al., 2018; Guérin et al., 2021). This is cumbersome and tedious work but often enough worth the effort if systematic uncertainties can be reduced or at least correctly expressed.

To fast forward, our discussion ended with adding a new function called `correct_PMTLinearity()` to 'Luminescence' (Kreutzer et al., 2025) available with v1.1.1 (2025-09-11). In this contribution, we provide the technical background and discuss the potential impact on equivalent dose estimates. The succinct version for impatient readers: signal correction is likely to have an effect, but accurately quantifying its impact is challenging due to the number of involved parameters.

2. Technical background

In a PMT module, incoming light produces free electrons via the photoelectric effect. These electrons are then multiplied in a multi-staged high voltage field. If the PMT operates in photon-counting mode, these electron avalanches form current pulses that can be digitally counted. The number of counts is determined by the flux of photons with energies within the wavelength detection range of the PMT. The lower limit of the count rate is defined by the dark current, which represents an unavoidable signal background even in the absence of light input. It is caused by a thermally induced leakage current in the photocathode. The upper limit is reached when the system stops to differentiate individual

pulses due to a high photon flux. This can result in either no output (paralysed mode) or in temporal or lasting blinding of the PMT (non-paralysed mode). The extent of the linear range depends on various factors, of which the pulse-pair resolution is the dominating one. The pulse-pair resolution is typically expressed in nanoseconds (10^{-9} s) and represents the shortest possible time span at which the system can distinguish individual pulses. If two pulses occur within this time span, the PMT will return only one count, thus underestimating the photon flux. The time span given by the pulse-pair resolution is also called detector dead-time.

As long as the count rate stays within the range of linearity, photon flux underestimation due to detector dead-times can be corrected using the formula

$$N = \frac{M}{1 - M\kappa} \qquad (1)$$

where N (s^{-1}) is the true count rate, M (s^{-1}) the measured count rate, and κ (10^{-9} s) the pulse-pair resolution, respectively, the detector dead-time. For more details, we refer to the freely accessible photomultiplier handbook by Hamamatsu (Hamamatsu Photonics K.K., 2017), from which we drew also most of the technical background above.

This is all but news and frequently encountered statements regarding the count linearity of particular PMTs often include dead-time correction. However, it does not imply that this correction is automatically applied. For instance, the Freiberg Instruments lexsyg systems (Richter et al., 2025) do not automatically correct for PMT dead-time non-linearity but use detector overload thresholds that can be defined in the firmware settings[1] individually for each detector. The obvious idea is to avoid non-linear counting altogether or at least limit the effects. Nevertheless, depending on the PMT module operated at the margins of those limits, a correction might still be worth looking into it.

In Table 1 we list the PMTs most found in the systems operated in our community. The ET Q9235QB is a standard option available in, e.g., Risø (Bøtter-Jensen, 1997), lexsyg (Richter et al., 2025), Daybreak (Bortolot, 2000), and the LF02 (Baly et al., 2023) systems. The other detectors are either of newer design (e.g., ET PDM9107 series) or have different detection wavelengths for the red or infra-red range, and are probably less commonly installed in readers. Except for the ET Q9235QB PMT, pulse-pair-resolution data required for the linearity correction are part of the technical information provided along with the modules by the manufacturers. For the ET Q9235QB, it depends on the chosen housing, respectively the counting module, which may differ. Therefore, for this model we have quoted an assumed value. The linear detection range and κ vary between detectors causing different linearity corrections as exhibited in Fig. 1.

If we were to compare only single luminescence signals, such as two quartz thermoluminescence (TL) curves, disregarding other effects, the correction according to Eq. 1 is

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[1] Line in the XML settings file:
`<cFIParameter Name="DetectorSelectorOverloadSettings" .../>`

Table 1: Specifications of selected photon-counting modules typically used in the luminescence-dating community.

Model	Detection window [nm]	Manufacturer	10 % count loss [s^{-1}]	Pulse-pair resolution [ns]	Reference
ET Q9235QB[a]	290–630	ET Enterprises	$> 10 \times 10^{6}$[a]	~ 25	ET Enterprise Ltd (2010)
PDM9107-AP-TTL PDM9107-USB	280–630	ET Enterprises	$\sim 3 \times 10^{6}$[b]	25	ET Enterprise Ltd (2017)
H7421-40[c]	320–720	Hamamatsu Photonics	$\sim 1.5 \times 10^{6}$	70	Hamamatsu (2008b)
H7421-50[c]	380–890	Hamamatsu Photonics	$\sim 1.5 \times 10^{6}$	70	Hamamatsu (2008b)
H7360-02[d]	300–650	Hamamatsu Photonics	6×10^{6}	18	Hamamatsu (2008a)

[a] Characteristics may differ with attached housing and counting module.

[b] After dead-time correction up to $100 \times 10^{6}\,\text{s}^{-1}$

[c] Model discontinued 12/2024, new series with comparable properties: H16721 (Hamamatsu, 2025)

[d] Model discontinued, suitable replacement with equal properties as above: H11870

straightforward, and the effect as shown in Fig. 1 is correctly quantified. However, typical measurement protocols used for D_e determination, such as the single-aliquot-regenerated (SAR) dose protocol (Murray and Wintle, 2000), involve more steps, and the physics of luminescence production (e.g., Bailey, 2001) does not provide a direct path to quantify the impact on the results. In other words, while Fig. 1 makes a compelling case, it is overly simplified because the effects in the D_e cannot be derived from single count values alone.

3. Simulation of equivalent dose impact

To simulate the ratio of D_e values determined with uncorrected and corrected signals, we simulated a SAR sequence using the R package 'RLumModel' (v0.2.11) (Friedrich et al., 2016) and the Bailey (2001) quartz model. With an assumed dose rate of $1\,\text{Gy}\,\text{s}^{-1}$ for the irradiation source, we added regeneration dose points up to 1,000 Gy for each experiment to ensure a similar dose-response curve (DRC) shape. The unusual size of the dose rate (compared to typical $0.1\,\text{Gy}\,\text{s}^{-1}$ in built-in irradiation sources) does not affect the outcome of our experiment. We then modified the given dose to be recovered to move theoretical points along the set of DRCs. The D_e was derived from DRCs obtained for dead-time non-linearity-corrected and uncorrected shine-down curves. For the correction, we used a κ of 18 ns as the lowest value in Table 1. To simulate different light levels, we used a factor $(0.0001, 0.0002, \ldots, 0.001)$ to reduce the intensity of the shine-down curves. This was less challenging than modifying the Bailey-model to obtain realistic magnitudes of count values as typically measured with PMT modules. However, it resulted in non-meaningful dark-count values as such simulation is typically not part of the model implementation. The latter was still acceptable because the modelling output using differential equations does not include stochastic uncertainties (see discussion in Pagonis et al., 2020). With that being said, the chosen settings (light level and κ) are not entirely arbitrary but best align with the Hamamatsu H7360-02 PMT operated in most of our lexsyg readers here in Heidelberg.

Our modelling sequence was defined with the following parameters:

```
sequence <- list(
  RegDose = <dose_points>,
  TestDose = 25,
  PH = 220, #preheat
  CH = 220, #cutheat
  OSL_temp = 125, #read temp.
  Irr_2recover = <given_dose>,
  OSL_duration = 70)
```

This sequence was then used by 'RLumModel' to simulate the corresponding DRC:

```
RLumModel::model_LuminescenceSignals(
  sequence = sequence,
  simulate_sample_history = TRUE,
  model = "Bailey2001",
  lab.dose_rate = 1,
  ...)
```

The full R script used for our simulation is attached as a supplement for detailed inspection. For this manuscript, Fig. 2 suffices and illustrates the basic concept of our simulation. For simplicity, we show only shine-down curves for one intensity setting, while the script produces a set of curves for each SAR sequence using different intensities for each particular dose to recover.

Figure 3 shows the output of our simulation. The primary x-axis and y-axis refer to the plotted but arbitrary values, while the secondary axes provide the conversion to physically meaningful quantities. For the x-axis, these are Gy and for the y-axis absolute signal intensity. This seems to contradict the given dose (primary x-axis), but indeed, with dose, the Bailey (2001) model-based simulated SAR protocol increasingly fails to recover the given dose; a model property unrelated to the applied dead-time correction. A similar pattern can be found for other quartz luminescence models that are included in 'RLumModel'.

The colours in the heatmap encode the obtained ratio of the corrected and uncorrected D_e values. The white solid contour lines provide guidance to better connect colours with the scales on the axes. For ratios > 1 the D_e derived from corrected shine-down curves is higher. For ratios < 1 the
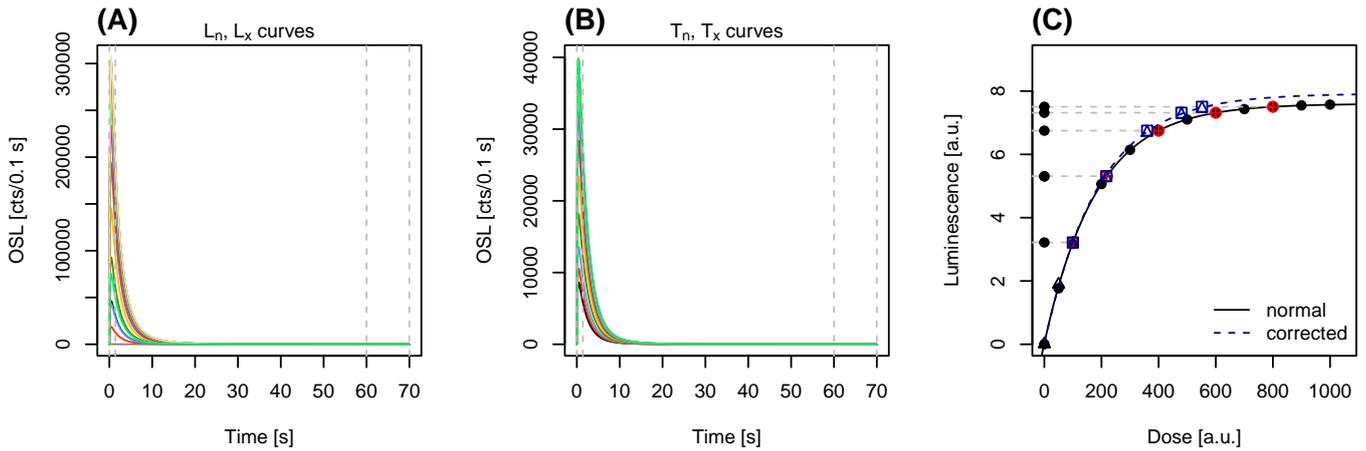
Figure 2: Typical simulated shine-down curves for L_x (A) and T_x (B) and the corresponding dose-response curve (C). In (C) we added the different L_n/T_n points for which different D_e values can be calculated either for the uncorrected signals (solid black line) or the DRC based on dead-time non-linearity corrected shine-down curves (dashed blue line). More details see main text.

corrected D_e is lower, which is the case for most simulated scenarios. This is because the correction of the shine-down curves causes less curvature of the DRC and the corresponding corrected D_e derived from such curves yields smaller values.

In our example, the calculated ratios between D_e values obtained with and D_e values obtained without correction, range from 0.92 to 1.01 in corner cases. Realistically, the difference between D_e values derived from uncorrected signals to D_e values based on dead-time non-linearity corrected signals will ballpark 1–2 %. For approximation, we assume that most quartz D_e values will be lower than 200 Gy in dating scenarios. Please note that ratios in Fig. 3 and as they may appear in Fig. 2 are not comparable, because the hypothetical DRC added as a dashed blue line in Fig. 2 would only exist for one scenario of a dose to be recovered.

During a SAR measurement, as simulated here, the light output can decrease or increase depending on the regeneration dose, preheat/cutheat temperatures, and sensitivity changes; all related to the process of luminescence production. SAR protocol tests, e.g., dose-recovery tests, and test dose measurements during the sequence should account and correct for this, given that light output readings are reliable and not affected by instrumental changes that are not part of underlying luminescence physics. Unfortunately, the number of parameters we can modify for this model and simulation alone is huge and the number of possible scenarios nearly infinite. Hence, the simulation demonstrates that instrumental aspects are better taken care of to avoid hard-to-quantify systematic uncertainties later.

4. When and how to apply linearity correction?

The simulation suggests small but non-negligible D_e overestimations, if samples with high signal yield are evaluated without PMT-linearity corrections. However, at what count values should we start to worry and look for a solution?

A simple marker is the first channel of the first OSL measurement (e.g., L_n in the SAR protocol). This data point is typically the one with the highest impact on the obtained D_e. In Table 2 we provide rule-of-thumb values to make an assessment of the situation. We calculated at which count value the count underestimation exceeds 1 % depending on the channel width and the employed PMT.

In cases, where non-linearity seems to become a concern, we have identified three possible solutions that can be applied; in parts combined.

1. **Monitor and manage light output:** The most effective method to prevent any potential issues is to adhere to the most straightforward principle: avoid operating detectors close to or beyond their specified count linearity. This can be achieved through various means, including increasing the detector to sample distance, reducing the stimulation intensity while prolonging the stimulation duration, or employing the most straightforward approach of adding neutral density filters. These filters can be as simple as home-made pin-hole filters. Altering the aliquot size for the sake of lower light output should be avoided, though.

2. **Record dead-time profiles:** The second-most effective solution appears to be the one outlined in the Risø handbook: Record a linearity profile (Risø DTU, 2021). If this is supported by the manufacturer, it gives complete control and establishes a distinct threshold above which signals should be discarded.

3. **Post-correction:** Once the signal has been recorded but a linearity profile has not been established for the detector, post-processing using the linearity correction routine becomes appropriate. In the 'Luminescence' package, we have integrated the function `correct_PMTLinearity()` as part of this contribution. The user can provide `RLum.Analysis-class` or `RLum.Data.Curve-class` objects as input, specify the
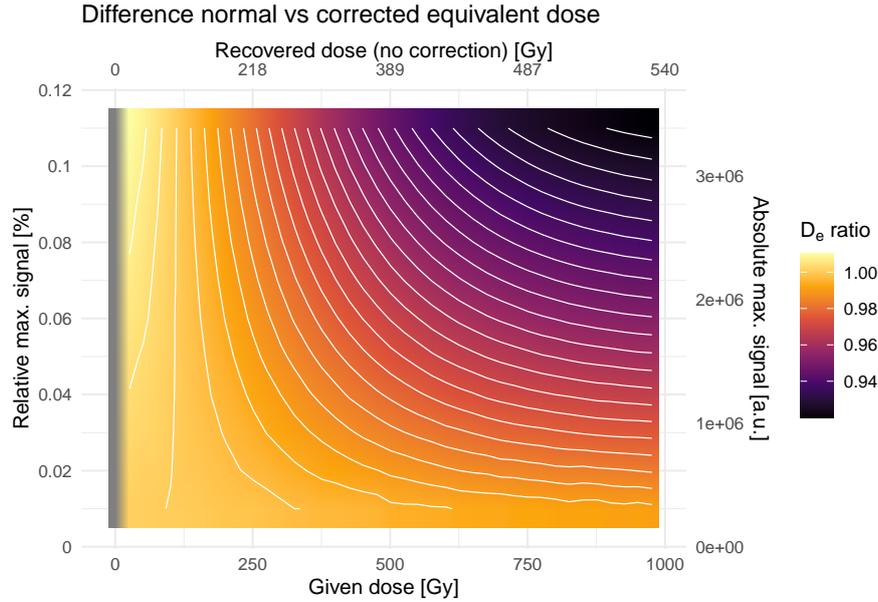
Figure 3: Simulated effect of signal strength and given dose on the difference of equivalent doses between the uncorrected and corrected signal. The secondary x and y-axes provide supplementary information on the recovered dose (x-axis) using the simulation for a specific given dose, and the expected absolute count value (y-axis), for which the unit can be assumed as $cts\,s^{-1}$. Please note that the numerical values depend on the model parameters of the simulation, and the graph serves solely as an indication of the anticipated impact. For further details, we refer to the main text.

Table 2: Counts per channel (CH) with an estimated difference of 1 % between measured and corrected value.

Pulse-pair-resolution	CH = 0.05 s	CH = 0.1 s	CH = 0.2 s	CH = 0.5 s	CH = 1 s	PMT examples
18 ns	27 778	55 556	111 111	277 778	555 556	H7360/H11870 series
25 ns	20 000	40 000	80 000	200 000	400 000	ET Q9235QB, PDM9107-APTTL series
70 ns	7 143	14 286	28 571	71 429	142 857	H7421/H16721 series

count-pair resolution, and then correction is performed automatically. If the input is an `.xsyg` file produced by a lexsyg reader, a new argument available through `import_Data(..., auto_linearity_correction = TRUE)` (through `read_XSYG2R()`) will attempt an automatic correction using count-pair resolution values for known detectors. However, while convenient, the automatic correction remains patchy, as not all versions of *LexStudio2* (the operating software for lexsyg readers) return information on the detector. In such cases, the manual call on `correct_PMTLinearity()` is the more reliable approach.

Solution 1 can be combined with either solution 2 or solution 3. In cases were dead-time profiles were established, no post-procession correction (solution 3) must be applied.

Finally, it should be noted that any solution relies on the non-paralysed operation mode of the PMT. If the PMT becomes dark in response to temporal overloads, the dead-time non-linearity correction will not be effective. On the other hand, a post-correction might be beneficial even in cases where only a fractional non-linearity might be expected to avoid systematic deviations and errors.

5. Conclusion and outlook

We discussed the well-known issue of non-linear counting of PMT modules commonly utilized for measuring luminescence. Our attempt to quantify the impact on the equivalent dose in SAR measurements would estimate a systematic uncertainty of up to 2 % for quartz OSL measurements even when using PMTs with a high pulse-pair resolution of 18 ns.

We propose managing the light output to mitigate such effects or recording linearity profiles. Alternatively, if this approach is not feasible, we suggest post-correcting luminescence signals using the new function `correct_PMTLinearity()` added to 'Luminescence'.

Our results are based on simulations with the objective of ensuring reproducibility and adaptation by others. Future work may necessitate re-analysing previously measured data to quantify the effect on the age and chronological inference for luminescence dating measurements.

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