Degradation of Signal-to-Noise Ratio in counting detectors due to pile-up effects

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This work proposes a methodology to investigate how the pile-up effect impacts detrimentally the signal-to-noise ratio of measurements taken by counting detectors. The method is presented from a conceptual point of view, justified and validated by both analytical and computer simulation methods. For this purpose, the ESRF detector Monte Carlo simulation tool was adapted to reproduce the behavior of theoretical pile-up models usually discussed in the literature.

The same approach was then applied to more complete 2D X-ray detection photon counting systems by including in the simulation all the primary physical effects and the full readout process of the detectors under consideration.

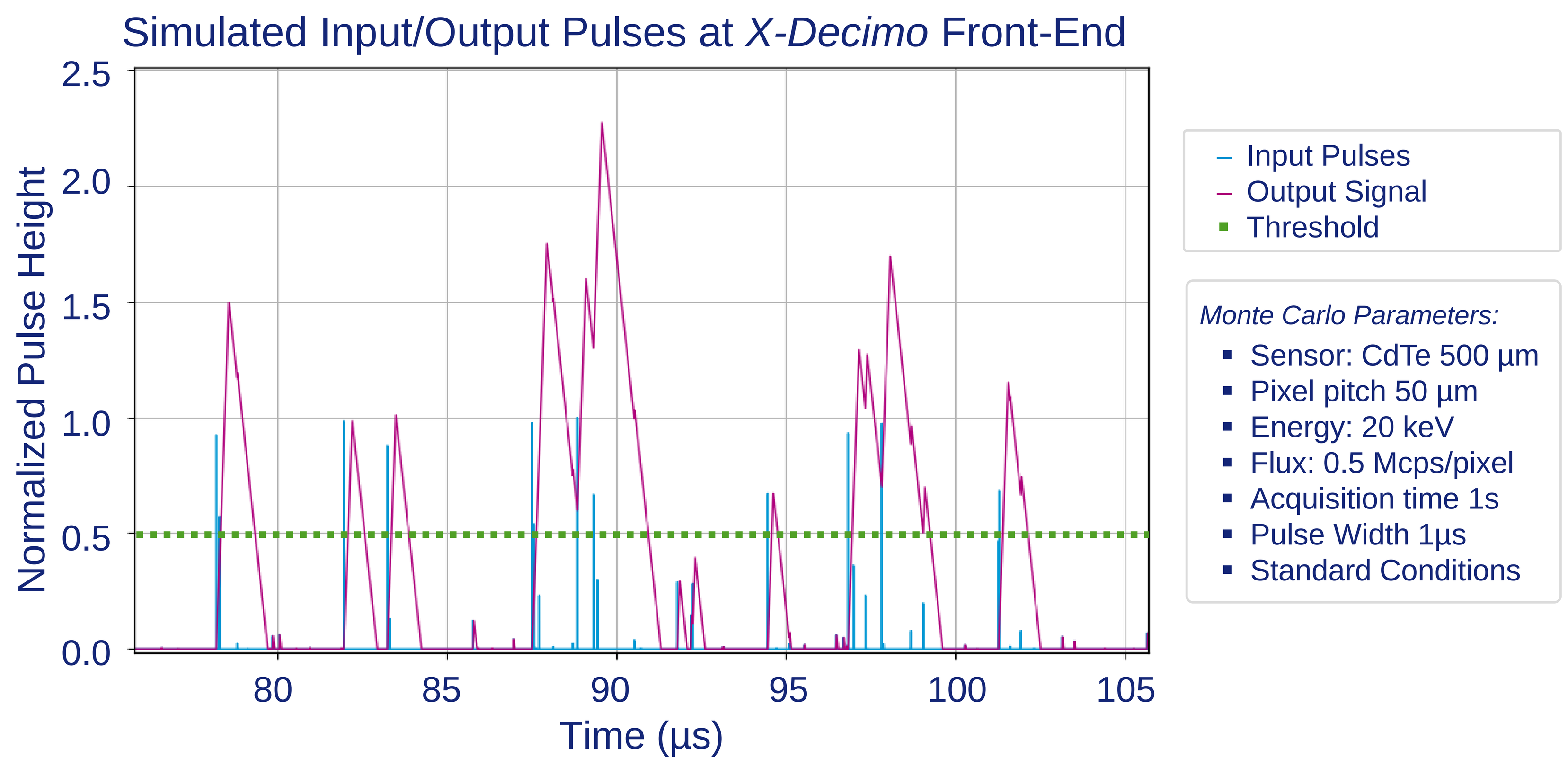
Introduction

Event counting systems: no dark counts, optimal for noise sensitive applications

Main limitation: high flux conditions ⇨ *pile-up effects*, leading to:

- Losses in efficiency and limited count rate capability
- Non-linear and non-Poissonian response

Several methods to minimize or compensate for the pile-up effects are being implemented, but rarely considering their impact on the statistical integrity of the produced data: the **SNR** of the measurement



Evaluation of the SNR

To estimate the SNR of a non-linear system, a **linearization correction** of the transfer function of the system (pile-up curve) is required.

- Numerically: obtain the pile-up curve and estimate the number of input counts from each measured output count-rate
  - ➢ SNR is obtained from the mean and standard deviation of the estimated input counts;
  - ➢ Is applicable to experimental or Monte Carlo simulated data
- Analytically: correction of the variance analytical expression for the *slope* of the pile-up curve at a given input count rate:

$$SNR_{\text{meas}}(count\ rate_{in})^2 = \left(\frac{counts_{in} \times slope(count\ rate_{in})}{\sigma(counts_{out})}\right)^2$$

Case Study: a Complete 2D X-ray Detector

The response of real counting systems does not follow the ideal models, and is not described by an analytical expression.

The numerical method was applied to *X-Decimo* front-end pulse processing model, which considers:

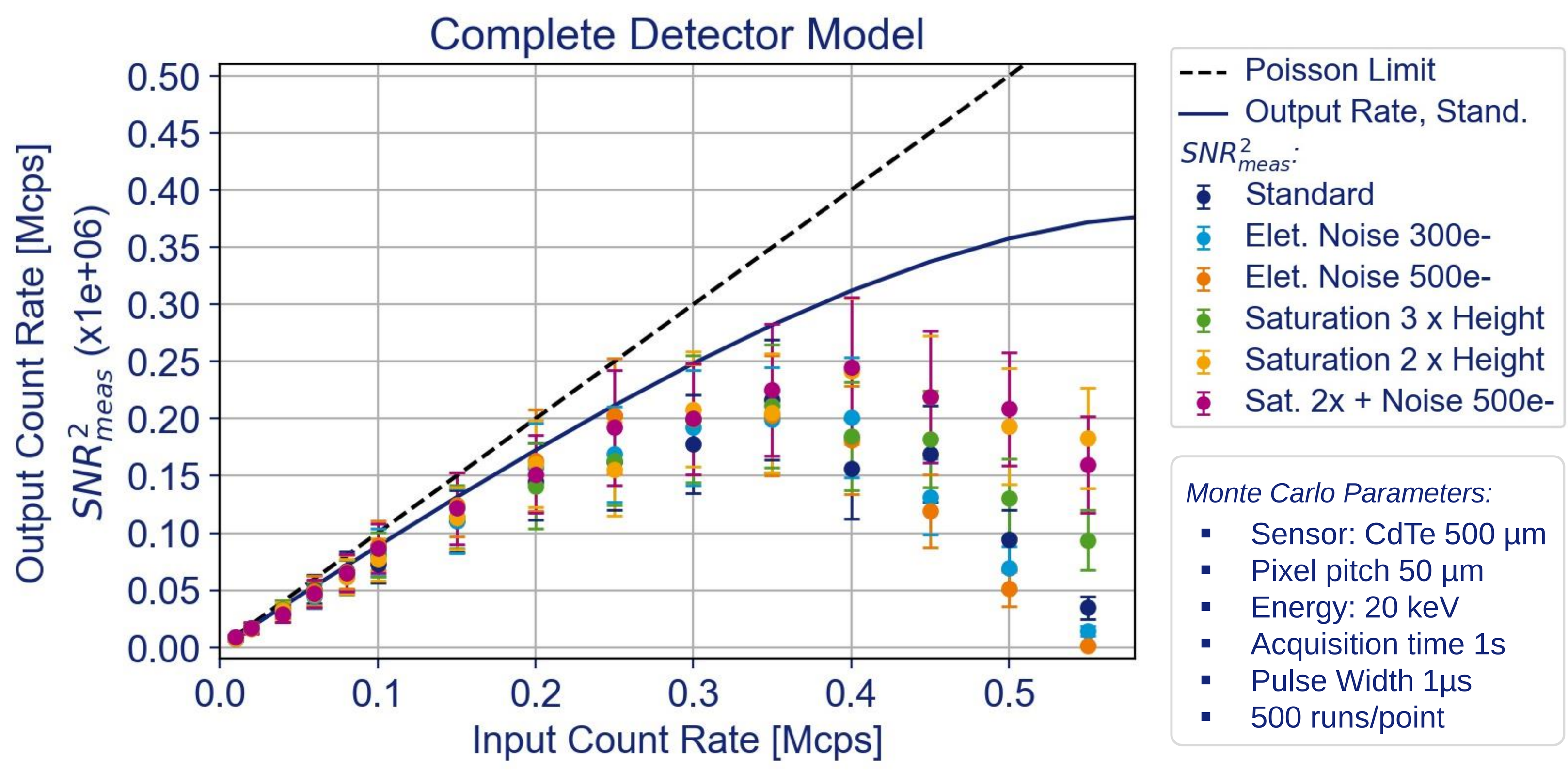
- X-ray events Poisson-distributed in time, variable input flux
- Photon-matter interactions in the detector sensor volume
- 2D pixel matrix with charge transport and pixel sharing effects
- Electronic noise and Amplifier saturation
- Triangular pulses of user-defined width and slope ratio
- Signal discrimination and standard pulse processing

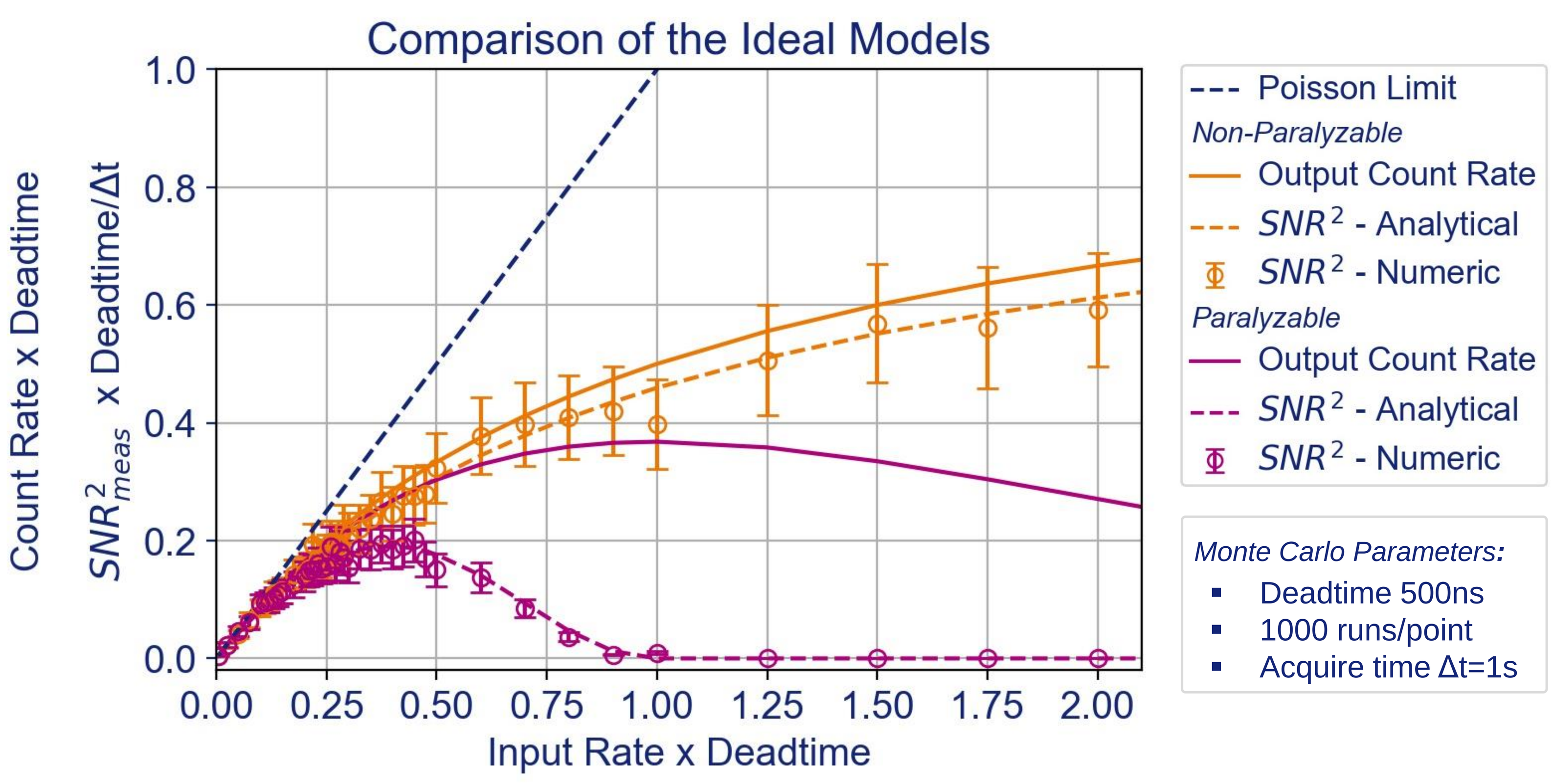
The simulation tool can then be used to evaluate and compare the impact of each parameter on the Signal-to-Noise ratio of the system:

Validation of the Method

The methodology was validated by comparing the analytical and numerical procedures:

- The analytical method was applied to the ideal **paralyzable** and **non-paralyzable** models, which have analytical formulas for mean and variance of the output counts[1];
- The numeric results were produced by the ESRF detector simulation tool *X-Decimo*[2] that was adapted to reproduce the behaviour of the ideal models.





Conclusions

- A method was established to verify the SNR of counting systems and the impact of individual detector parameters.
- The **SNR does not increase monotonically** with the count rate for paralyzable systems: it starts dropping and reaches zero when the output count rate saturates.
- This method can be applied to compare the impact of different pile-up compensation schemes on the resulting data statistics.

[1] D. Yu and J. Fessler, Phys. Med. Biol. **45** (2000), 2043–2056
[2] T. Johng-ay, P. Fajardo *et al*, Proceedings of 2016 IEEE NSS/MIC/RTSD, doi: 10.1109/NSSMIC.2016.8069944

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