Experimental evaluation of signal-to-noise ratio in counting detectors under pile-up conditions

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This work puts to the test a methodology to investigate how the pile-up effect impacts detrimentally the signal-to-noise ratio of measurements taken by counting detectors. As a follow-up from the previously presented study [1], the methodology was applied to experimental data taken at an ESRF bending magnet beamline with SPHIRD [2], an X-ray photon counting detector developed by an ESRF-AGH University collaboration that contemplates different pile-up compensation algorithms in the pixel logic.

Data processing methods were applied to compensate for the experimental artefacts related to the X-ray source. The SNR^2 of the standard counting mode presented a similar behaviour to the analytical response of a paralyzable counting system, and both tested pile-up compensation methods have presented a relative improvement in the statistical quality of the data.

Recap of the Methodology

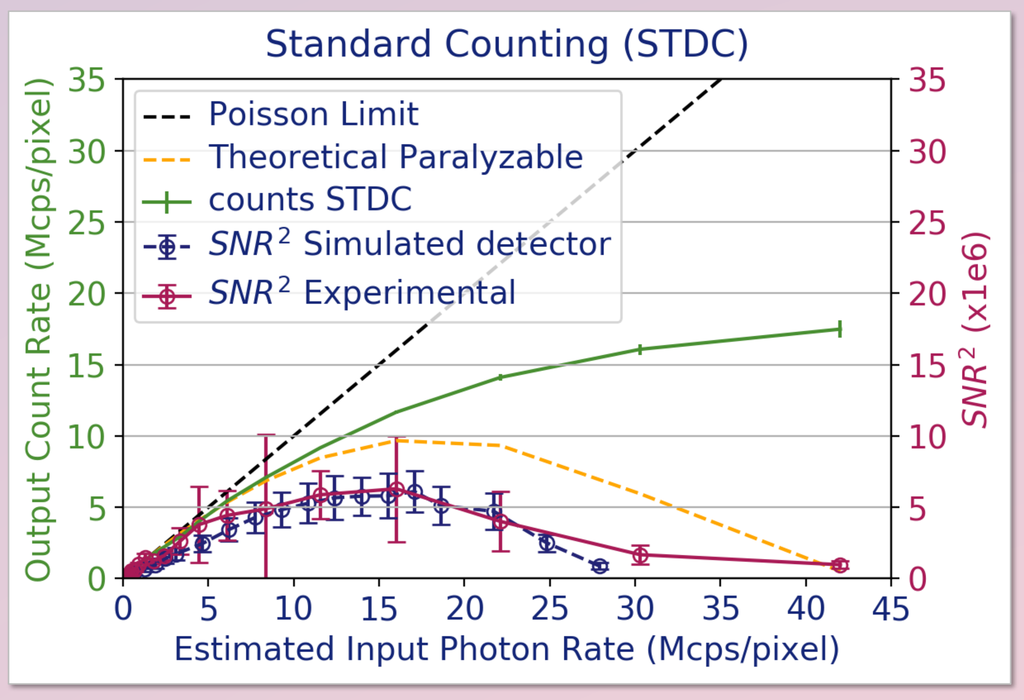
To estimate the SNR of a non-linear system, a **linearization correction** of the transfer function of the system (**pile-up curve**) is required.

- Numerically: obtain the pile-up curve and estimate the number of input counts from each measured output count-rate
  - The pile-up curve can be obtained by accessing the average output count rate with respect to the various input fluxes
  - For several measurements at a given input flux, use the pile-up curve to estimate the corresponding input counts
  - SNR is obtained from the mean and standard deviation of the estimated input counts
- Analytically: correction of the variance analytical expression for the *slope* of the pile-up curve at a given input count rate:

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

Response of a standard counting system

- The results shown here refer to the same single pixel
- Deadtime estimated via fitting: **21.1 ± 0.1 ns**
- SNR behaviour comparable to the ideal paralyzable model with same deadtime

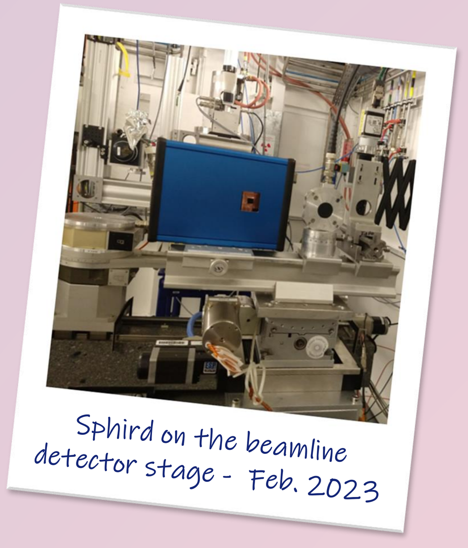


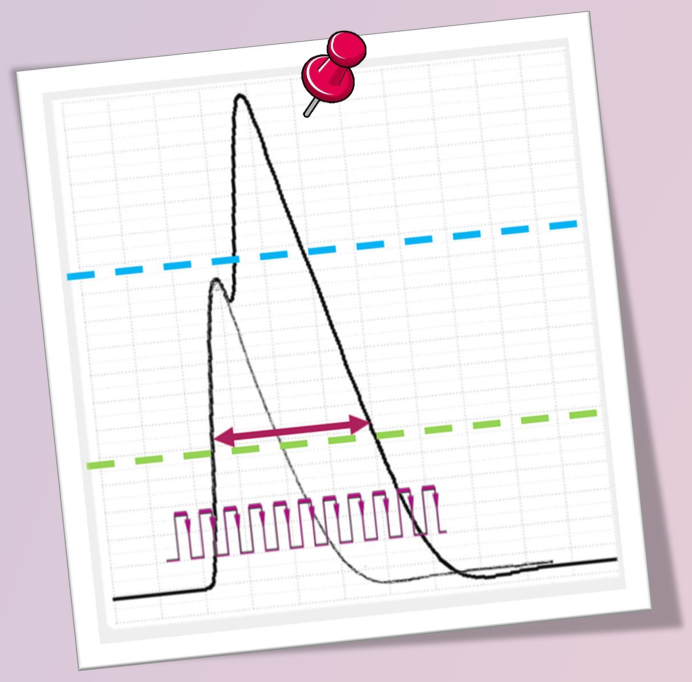
- Performance worse than the ideal model, but similar to the simulated realistic detector → **artefacts of the detection chain**

Simulated detector parameters:
- Si 400µm, -200V, 50µm pitch
- 500 threads
- 15 keV photons, TH at 50%
- Acq. time 0.05s
- Pulse width 20ns at the base
- Triangular pulses
- Elect. noise 180e⁻ RMS
- Saturation at 50 keV

Experimental Setup

- Detector under test: SPHIRD ASIC of 32x64 pixels, 50µm pitch, bonded to a silicon sensor 400µm thick
- Source: Direct 15 keV monochromatic multi-bunch beam from the ESRF X-ray beamline **BM05**, 1.0x0.5mm (20x10 pixels)
- Flux controlled with a set of Al filters, 60µm to 8mm
- 500 acquisitions per filter step, threshold at 7.5 keV (50% energy)



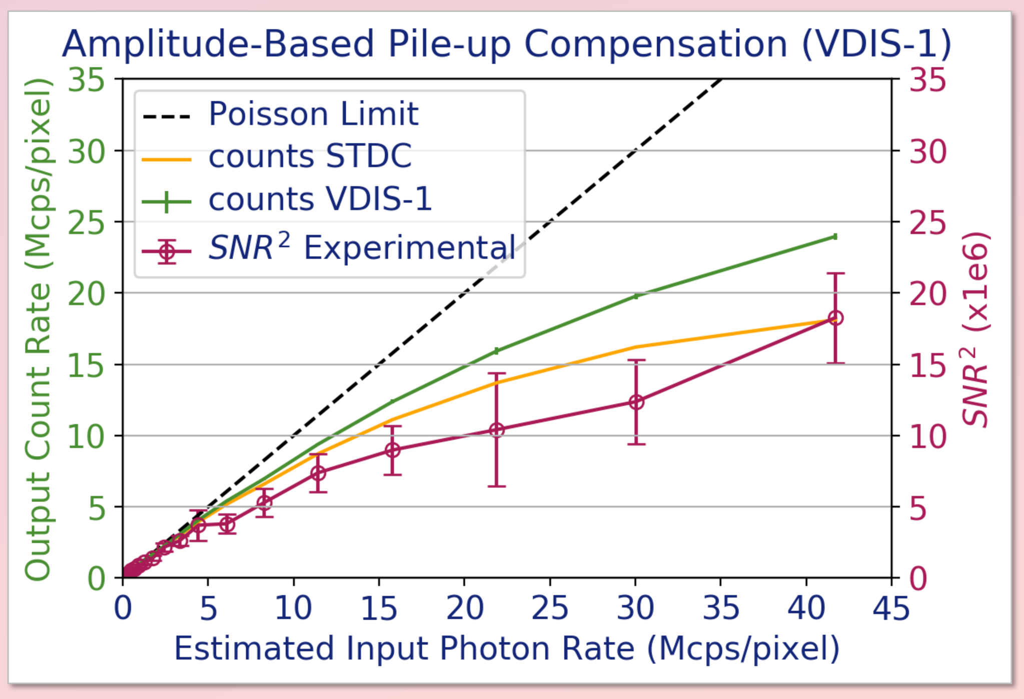


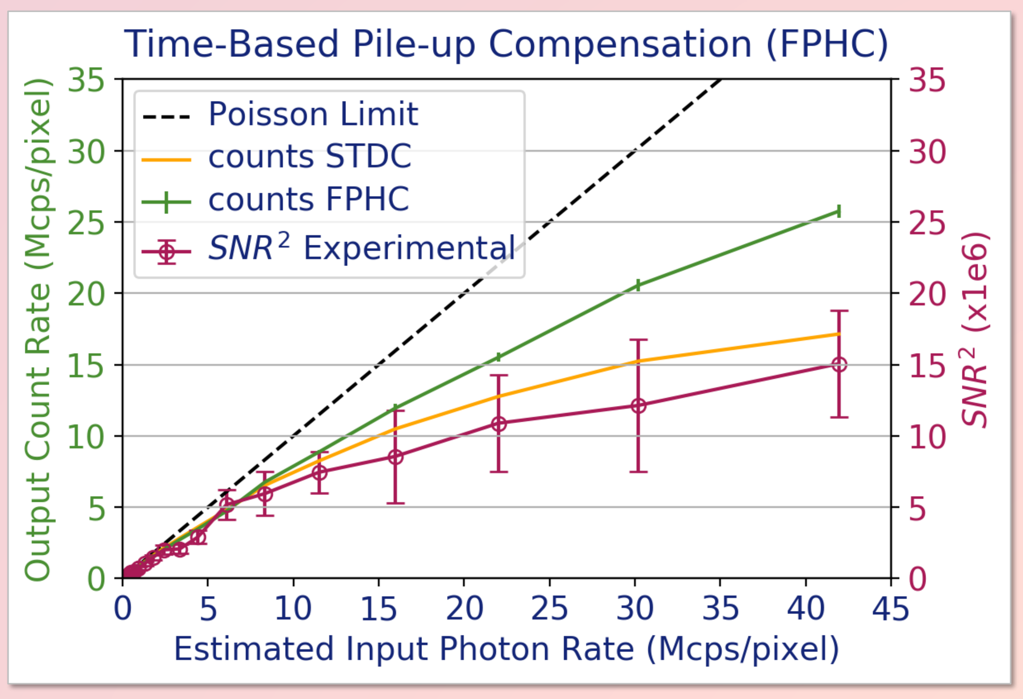
Pile-up compensation modes investigated:

- **VDIS-1**: pulse **amplitude** based
  - 1 extra threshold at 137% energy
  - The outcome is the sum of the 2 thresholds outputs
- **FPHC**: pulse **width** based
  - Measures the **ToT** with an asynchronous 200 MHz clock
  - Output normalized by the number of clock cycles in no pile-up conditions

Response of the pile-up compensation schemes

- Improvement of the count-rate performance
- Improvement of the data statistical quality (SNR^2)
- SNR^2 increases **monotonically** with flux up to 60% pile-up





- Time-based method (**FPHC**) was **better** in count-rate performance
- But statistically both had the **same effect on the SNR^2**

How to minimize the impact of beam instabilities

- Issue: The X-ray beam suffers from drifts and non-uniformities, resulting in time variations in the incident photon flux that degrade the SNR measurements.
- Processing method, for each step, for a given pixel (i, j):
  - Estimate the correspondent input counts $counts_{in}$ for each acquisition
  - Calculate the ratio $r_{i,j}$ between two consequent acquisition $counts_{in}$ values
  - Calculate the variance of the ratios $var(r_{i,j})$
  - Calculate the SNR:

$$SNR_{i,j} = \sqrt{\frac{2}{var(r_{i,j})}}$$

Conclusions

- A method was established to estimate the SNR of counting systems
- The method has proven to be **applicable to experimental measurements**
- Despite the experimental artefacts, it was possible to identify that the behaviour of the pile-up effect on the SNR^2 **matched the simulated predictions**, peaking around 30% pile-up and degrading after
- Both pile-up compensation modes investigated have demonstrated a **comparable improvement** of the system's response on the SNR

[1] D. Magalhaes and P. Fajardo, JINST 18 (2023), C01016
[2] P. Grybos *et al.*, IEEE Transactions on Circuits and Systems II: Express Briefs (2023)