Simulating the Counting Mechanism of PILATUS2 and PILATUS3 Detectors for Improved Count Rate Corrections

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Abstract. PILATUS systems are well established as X-ray detectors at most synchrotrons. Their single photon counting capability ensures precise measurements, but introduces a short dead time after each hit, which becomes significant for photon rates above a million per second and pixel. The resulting loss in the number of counted photons can be corrected for by applying corresponding rate correction factors. This article presents a Monte-Carlo simulation, which computes the correction factors taking into account the detector settings as well as the time structure of the X-ray beam at the synchrotron. For the PILATUS2 detector series the simulation shows good agreement with experimentally determined correction factors for various detector settings at different synchrotrons. The application of more accurate rate correction factors will improve the X-ray data quality at high photon fluxes. Furthermore we report on the simulation of the rate correction factors for the new PILATUS3 systems. The successor of the PILATUS2 detector avoids the paralysation of the counter, and allows for measurements up to a rate of ten million photons per second and pixel. For fast detector settings the simulation is capable of reproducing the data within one to two percent at an incoming photon rate of one million per second and pixel.

1. Introduction
X-ray diffraction experiments greatly profit from the usage of hybrid pixel detectors, which allow for high dynamic range, low noise performance, high frame rates, as well as radiation tolerance. Their ability to exactly measure the number of photons guarantees for very precise data, but also introduces some dead-time during which the pixel is insensitive for incoming photons. For the PILATUS detectors, this dead-time is in the order of some hundred nanoseconds, which becomes significant when the incoming photon rate exceeds $10^6$ counts per second (cps). As a consequence the observed number of photons will be lower than the actual number of incoming photons. Fortunately this effect can be corrected for by applying rate correction factors as long as the observed rate monotonically increases with the incoming rate.

Assuming a paralysable or non-paralysable detector model, the rate correction factors can be derived analytically if the time interval between two photon bunches is constant. For more complicated synchrotron time structures, there exist no analytical solutions. In these cases Monte-Carlo simulations can be used to derive the correction factors. It turns out that PILATUS
systems are neither exactly paralysable nor non-paralysable. To correctly take into account the complex behaviour of its readout chip a detailed circuit simulation of the readout chip is required.

2. The PILATUS detector system
The PILATUS system basically consists of a 320 µm thick silicon sensor, which is electrically connected to a CMOS readout chip. Thicker sensors are available but are not investigated in this article. The absorption of the X-ray photons in the silicon leads to the creation of electron-hole pairs. Due to an applied bias voltage of 150 V the holes drift towards the collecting anode. Each sensor pixel is electrically connected to a cell of the readout chip, which is responsible for the amplification and registration of the signals. The collected charge is first amplified by the charge sensitive preamplifier. The gain of this preamplifier can be adjusted by a control voltage called $V_{rf}$. Subsequently the signal is formed by the shaper stage, whose control voltage $V_{rfs}$ is usually kept fixed. The output of the shaper is then compared to an adjustable threshold controlled by the voltage $V_{cmp}$. As long as the shaper output exceeds the threshold level the output of the pulse generator remains at high level. During that time, the corresponding pixel is unable to register further photons, which leads to the limited count rate capability. In contrast the readout chip of PILATUS3 systems has the ability to retrigger the output of the pulse generator after a fixed time, leading to a non-paralysing behaviour.

3. Simulation
The rate correction factors of the PILATUS pixel detectors depend on the detector settings, such as the gain of the charge sensitive preamplifier, the energy threshold, the retrigger time (PILATUS3 only), as well as on the energy and time structure of the X-ray beam. To determine the correction factors as a function of these parameters, a simulation of the data acquisition process has been set up. The computation of the observed count rate for a given incoming photon rate proceeds along the following steps [1]:

(i) Generating the temporal sequence of the incoming photons.
(ii) Deriving the charge collected by a pixel as a function of time.
(iii) Simulating the response of the readout chip to this charge.

In the following the term incoming rate will refer to the photon rate as it would be determined by the PILATUS detector in absence of any counting loss due to high photon rates.

4. Validation
4.1. Preamplifier Gain Dependency
The dead time of the PILATUS detectors is mainly determined by the preamplifier gain settings. A high gain results in a broader pulse, which paralyses the comparator for a longer time. Therefore the observed count rate will be lower for higher gain settings.

To study the gain and threshold dependencies of the rate correction factors, several datasets were acquired at the Swiss Light Source (SLS) at the Paul Scherrer Institute (PSI) in Villigen with PILATUS2 detectors [3]. This data has been analysed to validate the Monte-Carlo simulation described above. It is found that the simulation tends to count faster than the actual readout chip. The particular reason for this deviation between simulation and experiment is currently not known. The simulation can be brought into agreement with the measurements by adding a constant offset of 34 mV to the gain control voltage $V_{rf}$. This empirical value is used for all simulations presented in this article. After this calibration of the simulation, the difference between simulation and the experimental data (averaged over all investigated pixels) is around 2 percent in the high count rate region ($> 5 \times 10^5$ cps), cf. Figure 1.
4.2. Energy Threshold Dependency
A higher energy threshold decreases the time during which the pulse is above the comparator threshold voltage. This decreases the detector dead time and consequently increases the observed count rate. This effect is clearly observed in the SLS data. Figure 2 shows the measured data in comparison to the predictions of the implemented simulation. The simulation precisely predicts the observed count rate as a function of the energy threshold.

4.3. Time Structure Dependency
To study the dependency on the time structure of the X-ray beam, additional data sets were taken at the Australian Synchrotron (AS) with a PILATUS2 detector [2]. To maximise the detector count rate capability, the time between two electron bunches was adjusted to be slightly larger than the detector dead-time. Given the time period of the synchrotron of 720 ns, the three and four bunch modes result in bunch separations of 240 ns and 180 ns. A reference data set was taken in the default bunch mode with 2 ns bunch spacing, whose current follows a trapezoidal shape as a function of time.

Figure 3 shows that for the optimised bunch structures the observed rate is still increasing for incoming rates beyond $10^7$ photons per second and pixel. An important difference to the SLS data shown in the Figures 1 and 2 is the fact that the measured AS data is based on only one pixel. This might explain the larger deviation between data and the simulation (up to 7%), which reproduces the behaviour of an average pixel. From the SLS data it is known that the dead-time of different pixels varies on the order of ten percent.

4.4. Measurements with the new PILATUS3 system
For a PILATUS3 system, the combined dependency on the detector settings (gain, energy threshold and retrigger time) has been validated with continuous X-ray radiation from a Cu-tube. For each energy threshold, the internal threshold voltage and the gain settings of the detector was set as low as possible without picking up too much noise hits. The retrigger time was adjusted to be long enough to avoid double counting of single photons. The comparison between simulation and data is shown in Figure 4. For high threshold values (corresponding to low gain values) the simulation fits the data up to higher incoming rates than for lower threshold values (corresponding to higher gain settings). For fast settings the simulation is capable of reproducing the data within 1-2 percent for an incoming rate of $10^6$ cps. Up to an incoming rate of $10^7$ cps, the deviation stays below 5 percent. The PILATUS3 measurements have been performed with a prototype of the readout chip and should be considered as preliminary.
5. Results and Conclusions

Figures 5 and 6 show the observed count rates for PILATUS2 and PILATUS3 detectors for different operating modes of the European Synchrotron Radiation Facility (ESRF) as predicted by the Monte-Carlo simulation. There are two modes, labelled 992 bunches and 7/8+1 filling, for which the PILATUS detector behaves as if it sees a continuous X-ray beam. The modes 2*1/3 filling and 24*8+1 filling include some gaps in the X-ray flux. Compared to the continuous case the photons are squeezed to shorter intervals resulting in more pile-up and therefore lower count rates for the same incoming rates. The favourable mode with 16 bunches per circulation period has a bunch separation of 176 ns. The most disadvantageous mode involves only four bunches separated by 704 ns. PILATUS3 systems have a reduced dependency on the time structure and can clearly be operated to higher photon fluxes. The usage of detector settings and time structure dependent correction factors derived from the presented simulation will further improve its data quality at high photon fluxes.

References
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