

High performance X-Ray spectroscopy

With Programmable Systems on Chip

Electromagnetic Radiation Spectrum

Speed of light in vacuum
 $C \approx 3 \times 10^8 \text{ m/s}$

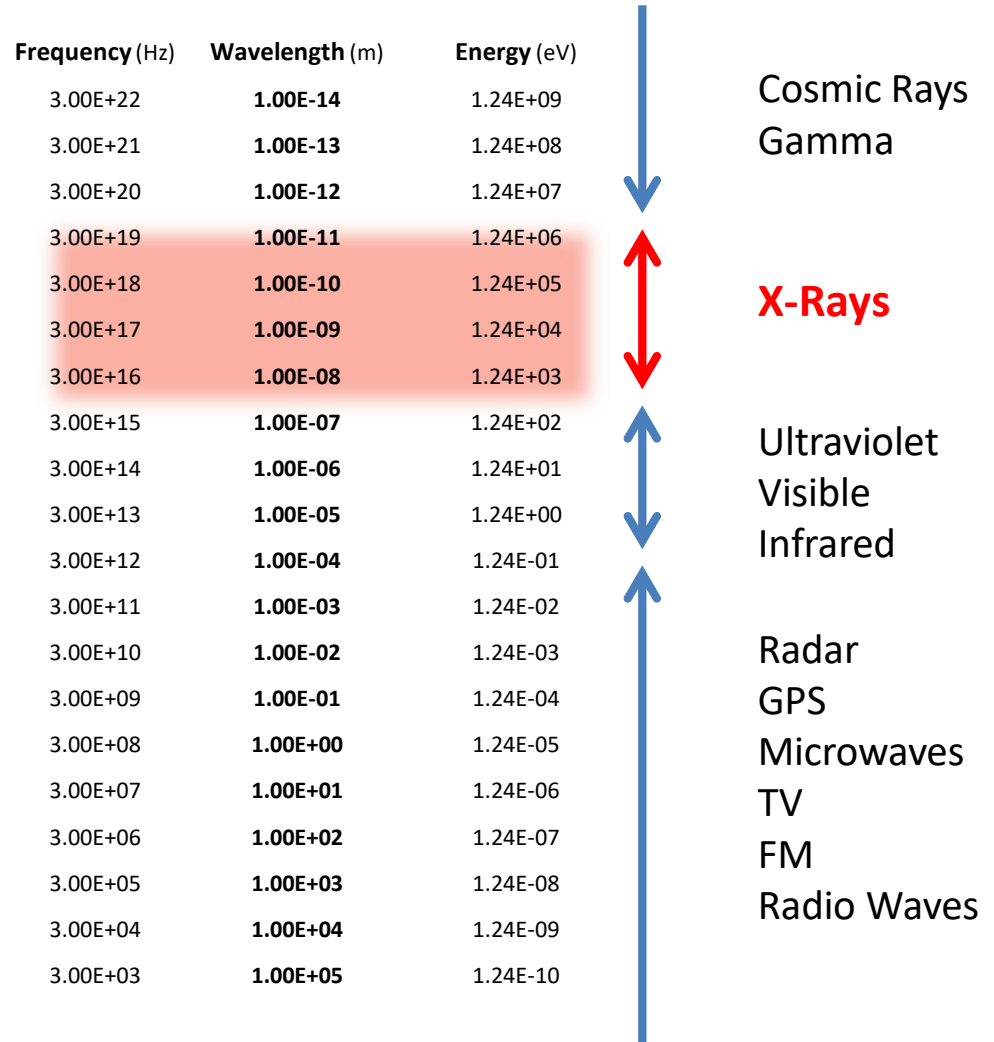
$$C = \lambda f$$

Quantization of energy,
 wave- particle duality,

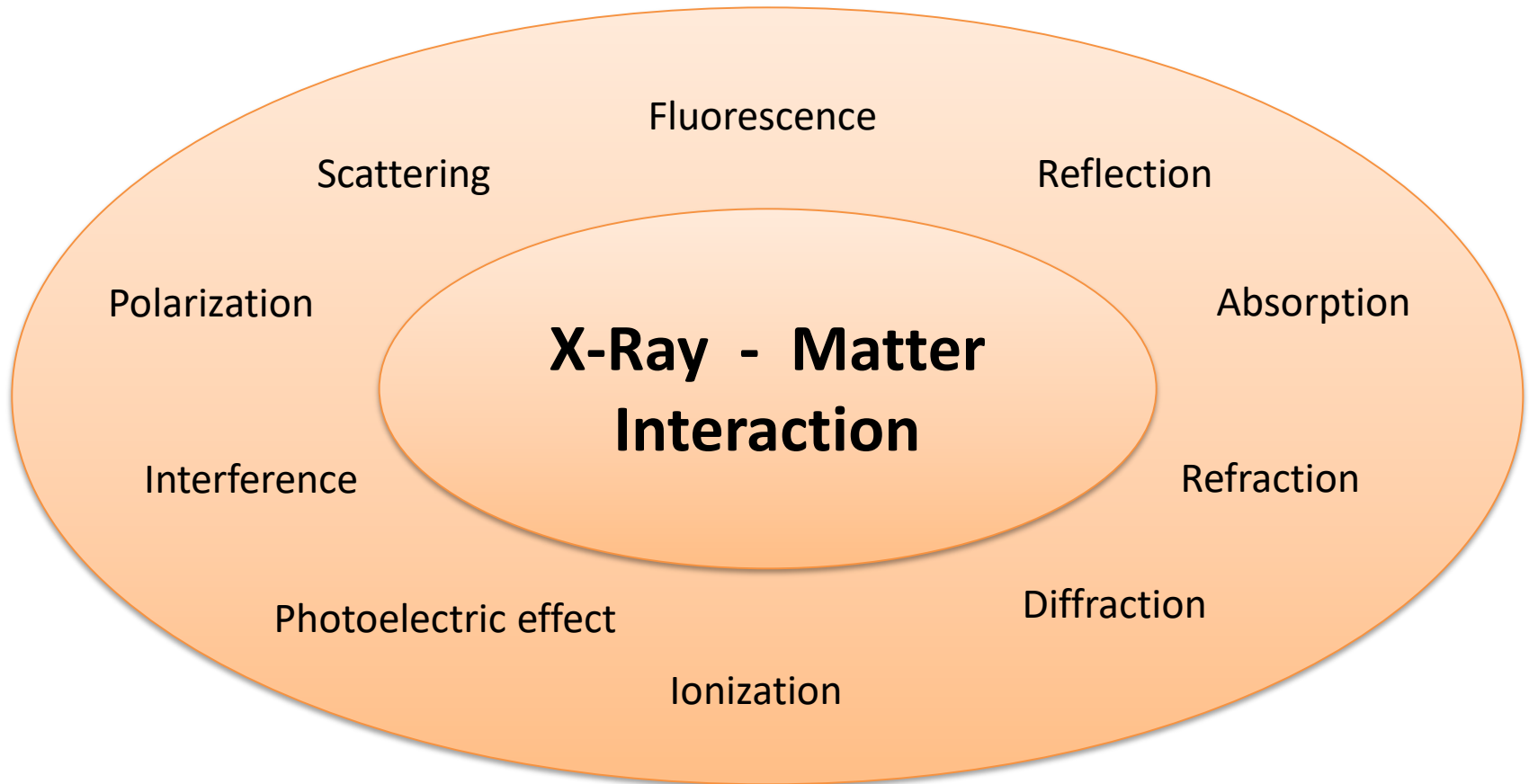
Planck's Law:

$$E = hf$$

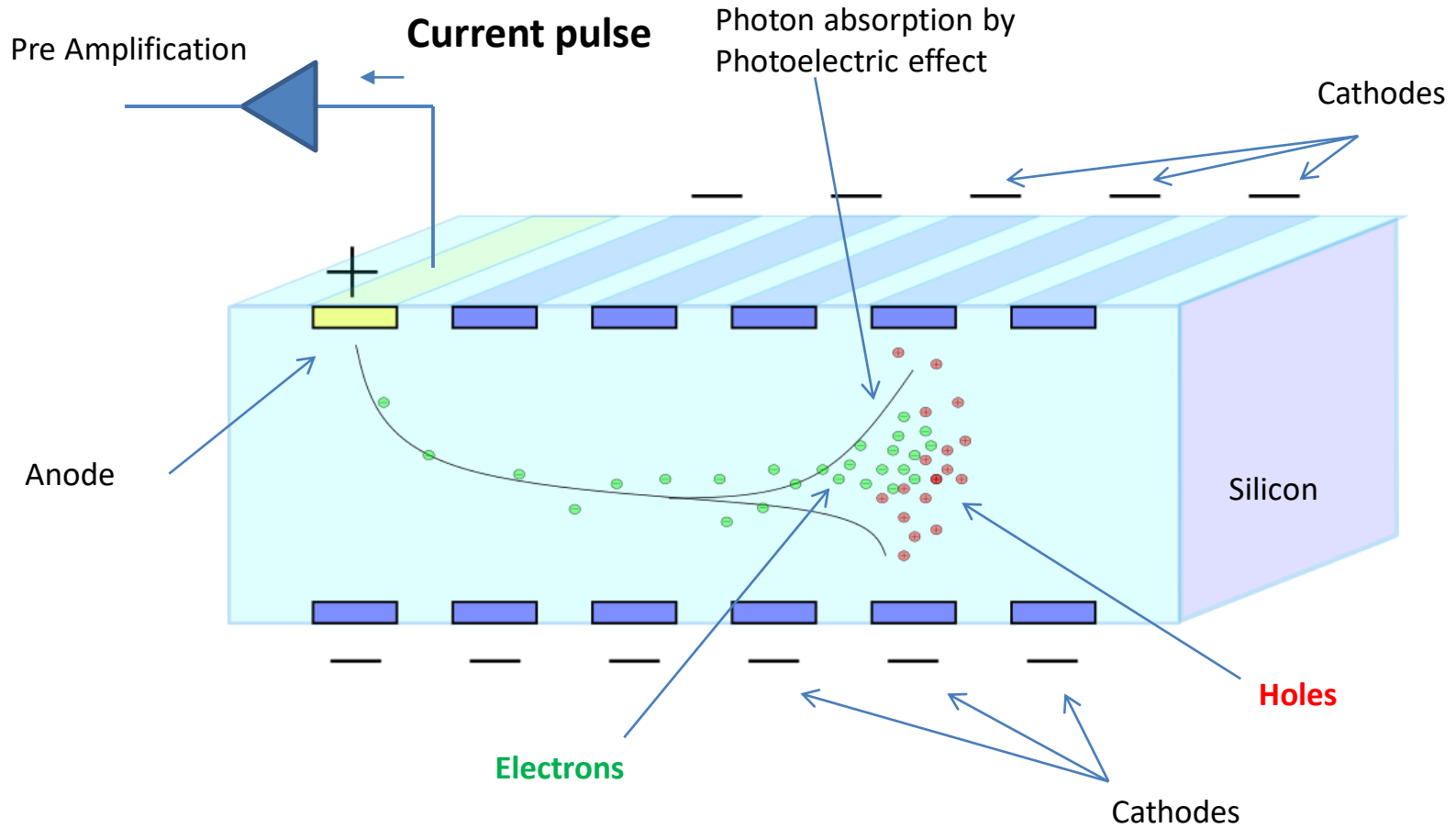
where $h = 4.135 \times 10^{-15} \text{ eV seconds}$



X-Ray Photons



X-Ray Photons Detection

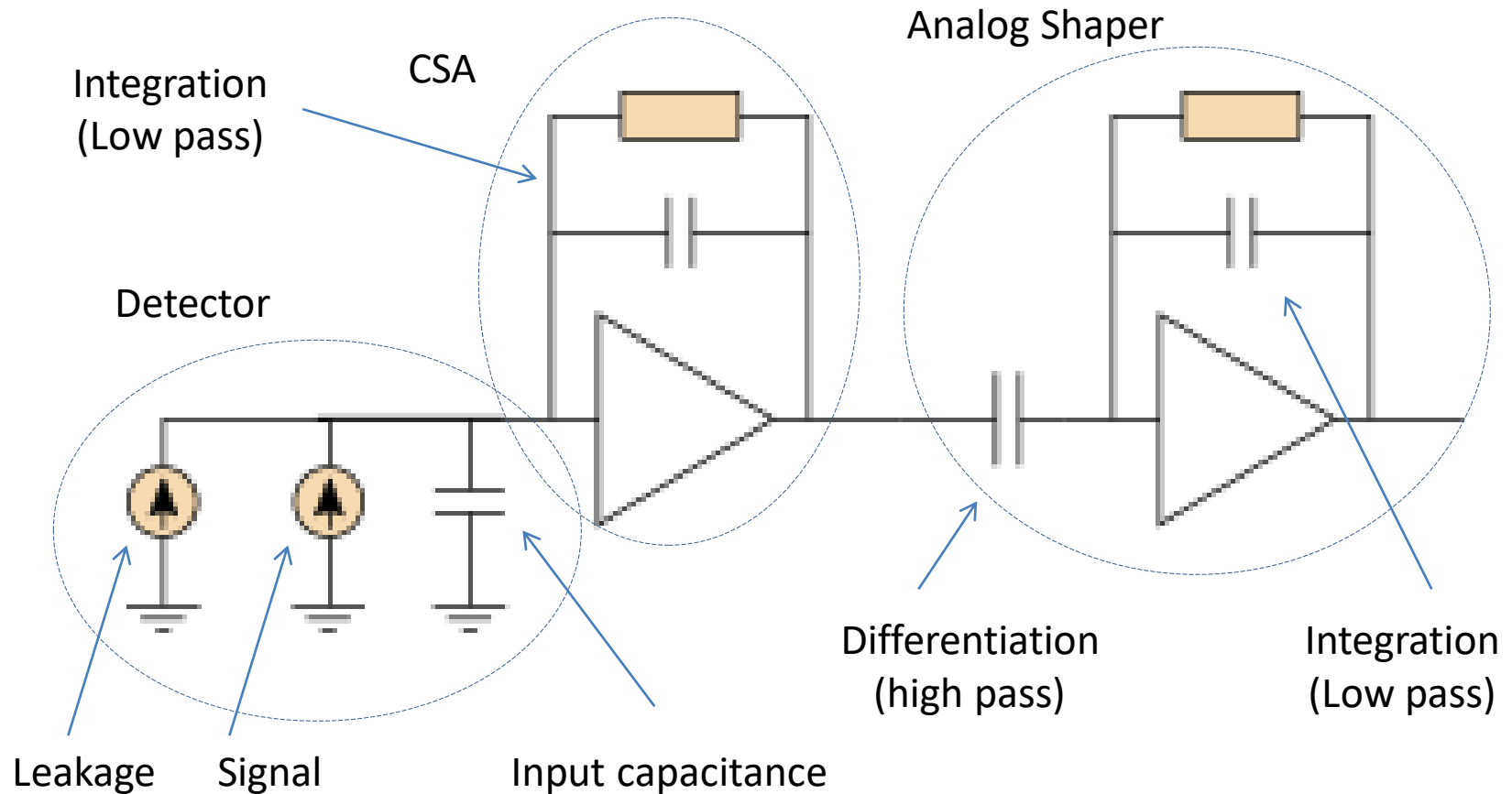


Digital Pulse Processing

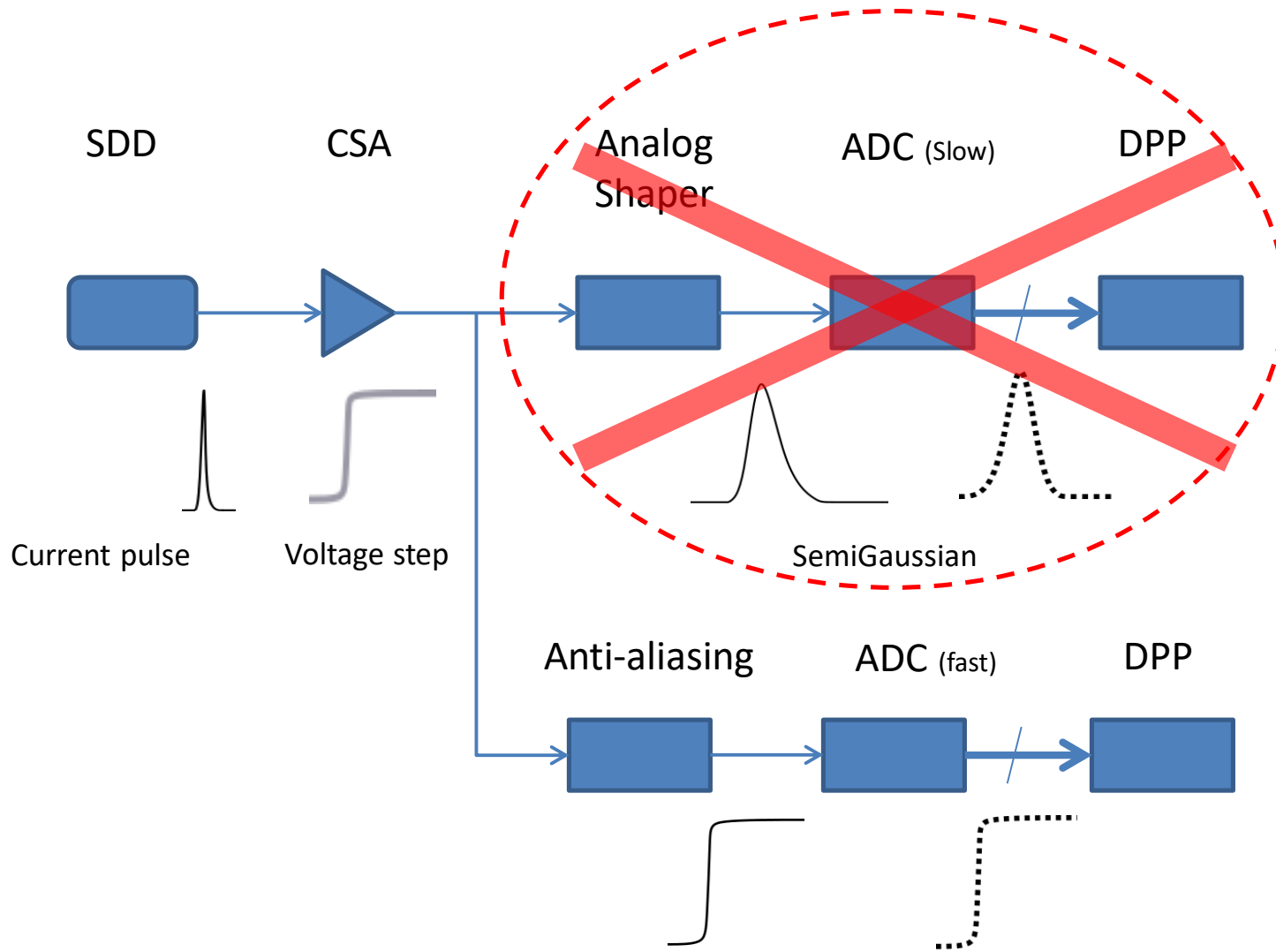
Desirable features in modern X-Ray spectroscopy

- Single photon detection capability
- High energy resolution
- Extended energy range
- High photon counting rates
- Effective and efficient pile-up rejection capability
- High time resolution and time-stamping capability
- Adaptability to different requirements and experimental conditions such as
 - Flexible tradeoffs between energy resolution and detection efficiency
 - Possible optimization to different noise conditions and signal shapes

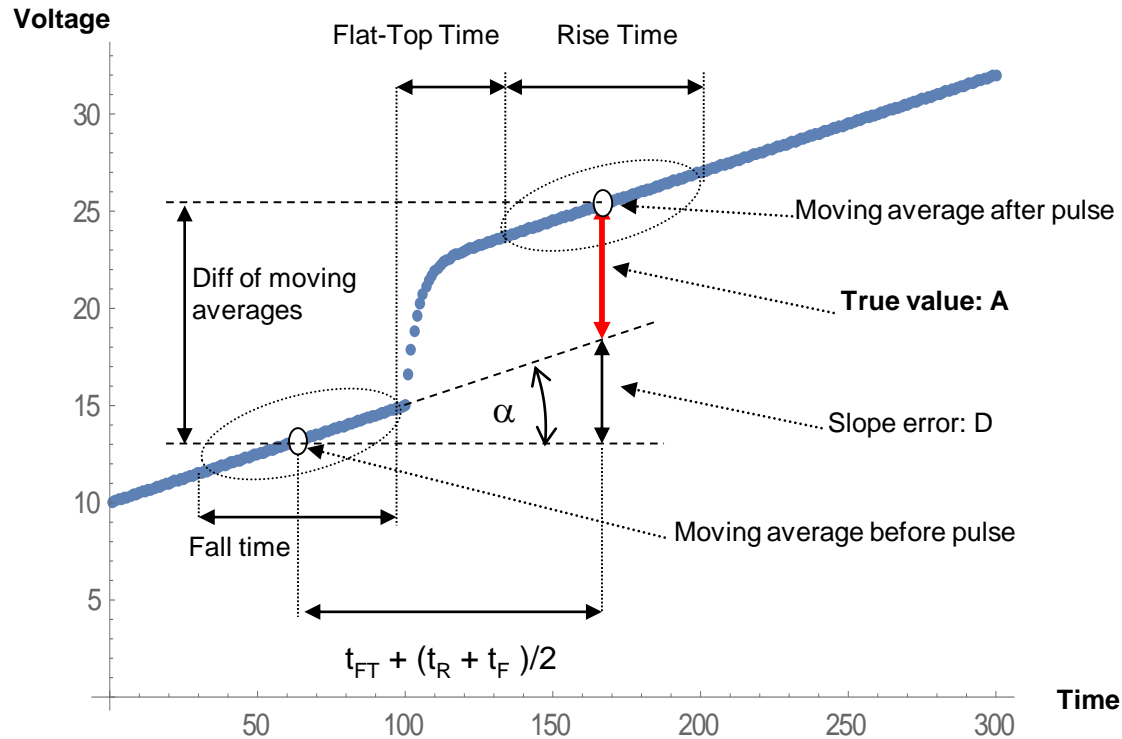
Detector, CSA, Pulse Shaper



Pulse Processing Chain



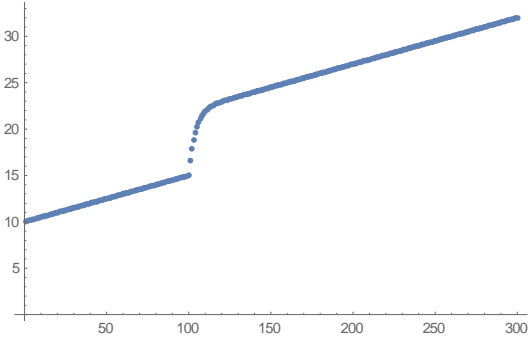
Time Domain Analysis of a Typical Voltage Step



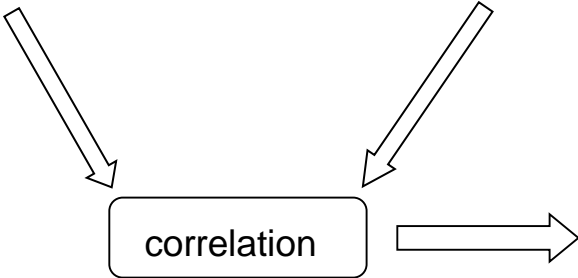
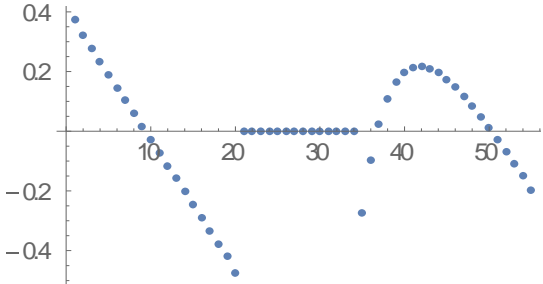
The true value can be calculated by mean of additions and multiplications

Digital Pulse Processing I: Measuring Amplitudes

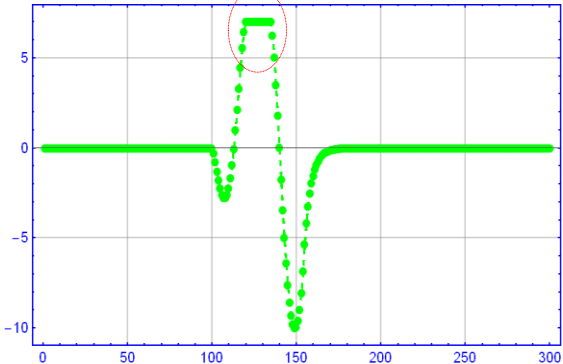
Input data



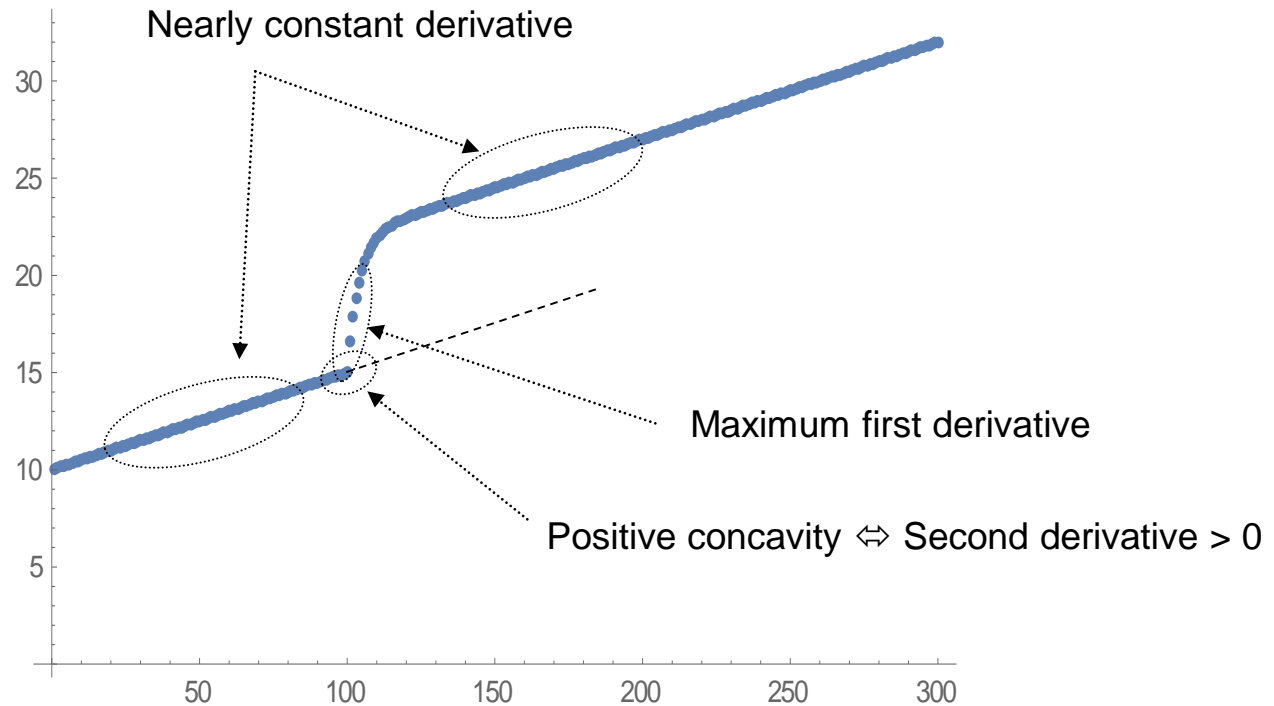
FIR Coefficients



Nearly perfect flat top



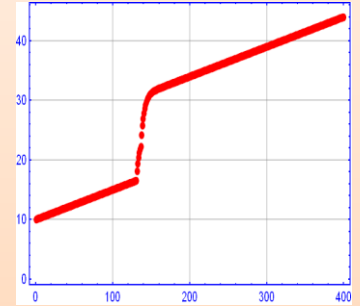
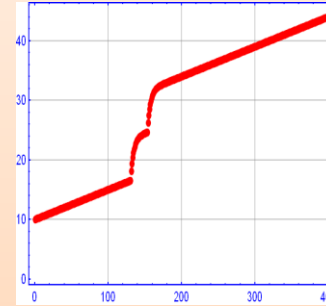
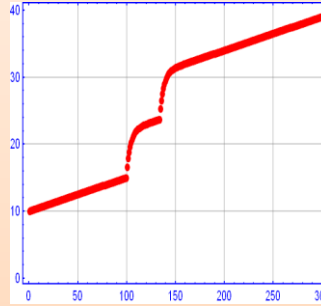
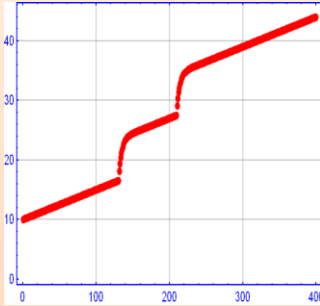
Digital Pulse Processing II: Detecting Arrival Times



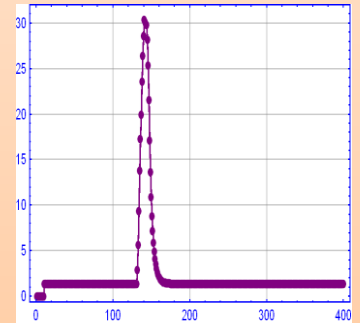
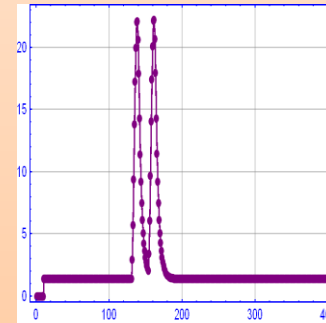
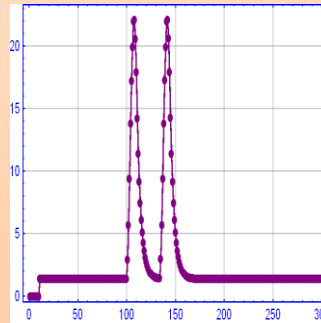
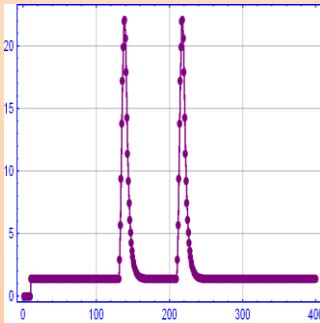
A short FIR can compute different discrete derivatives

Digital Pulse Processing III: Pile-up Rejection

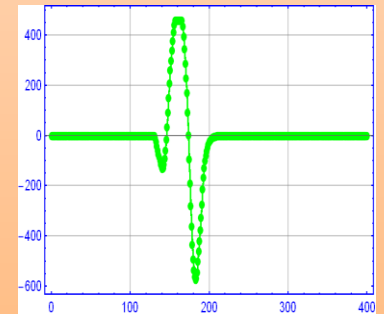
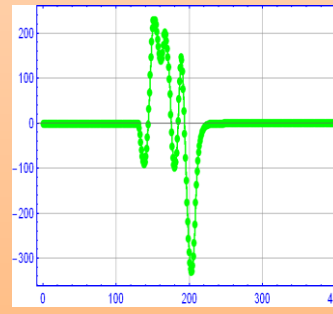
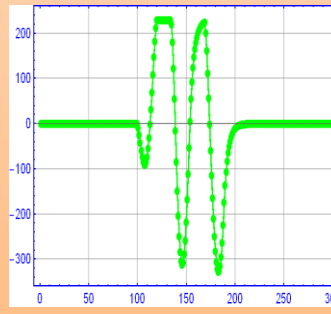
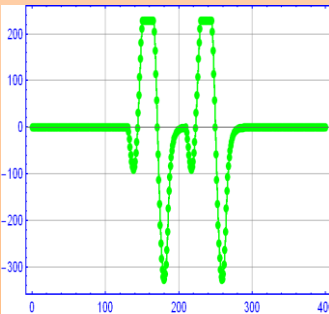
Input Pulses



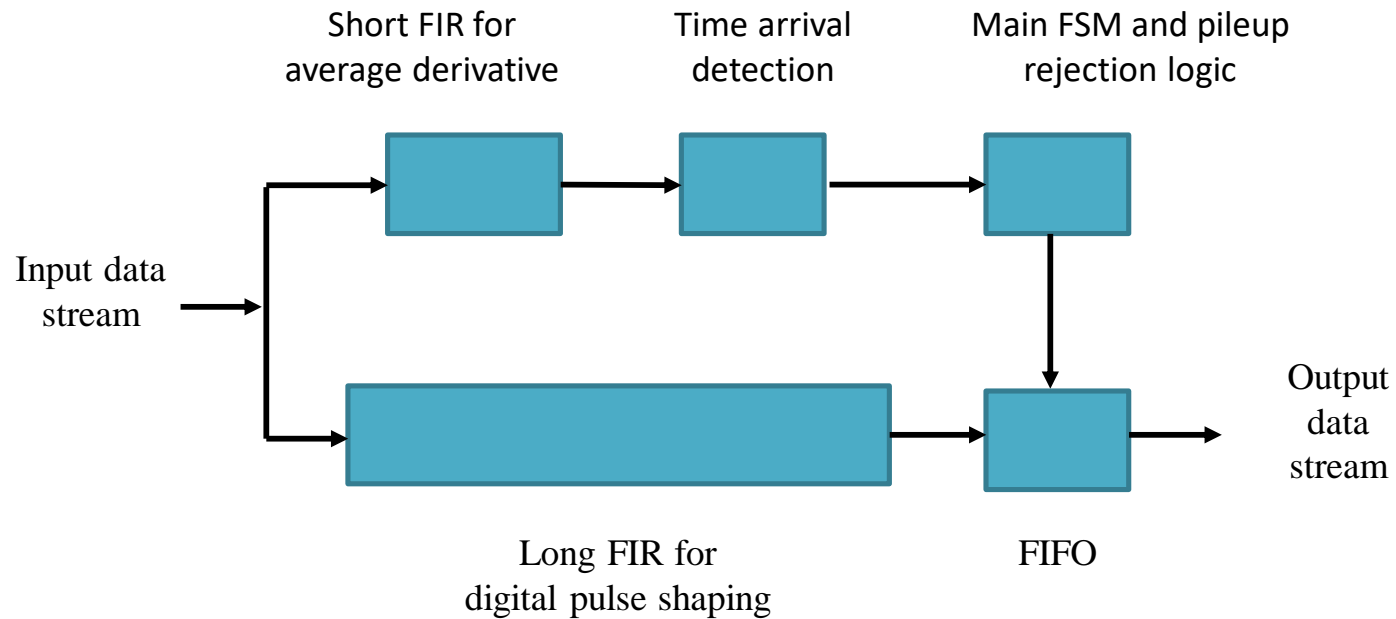
First Deriv



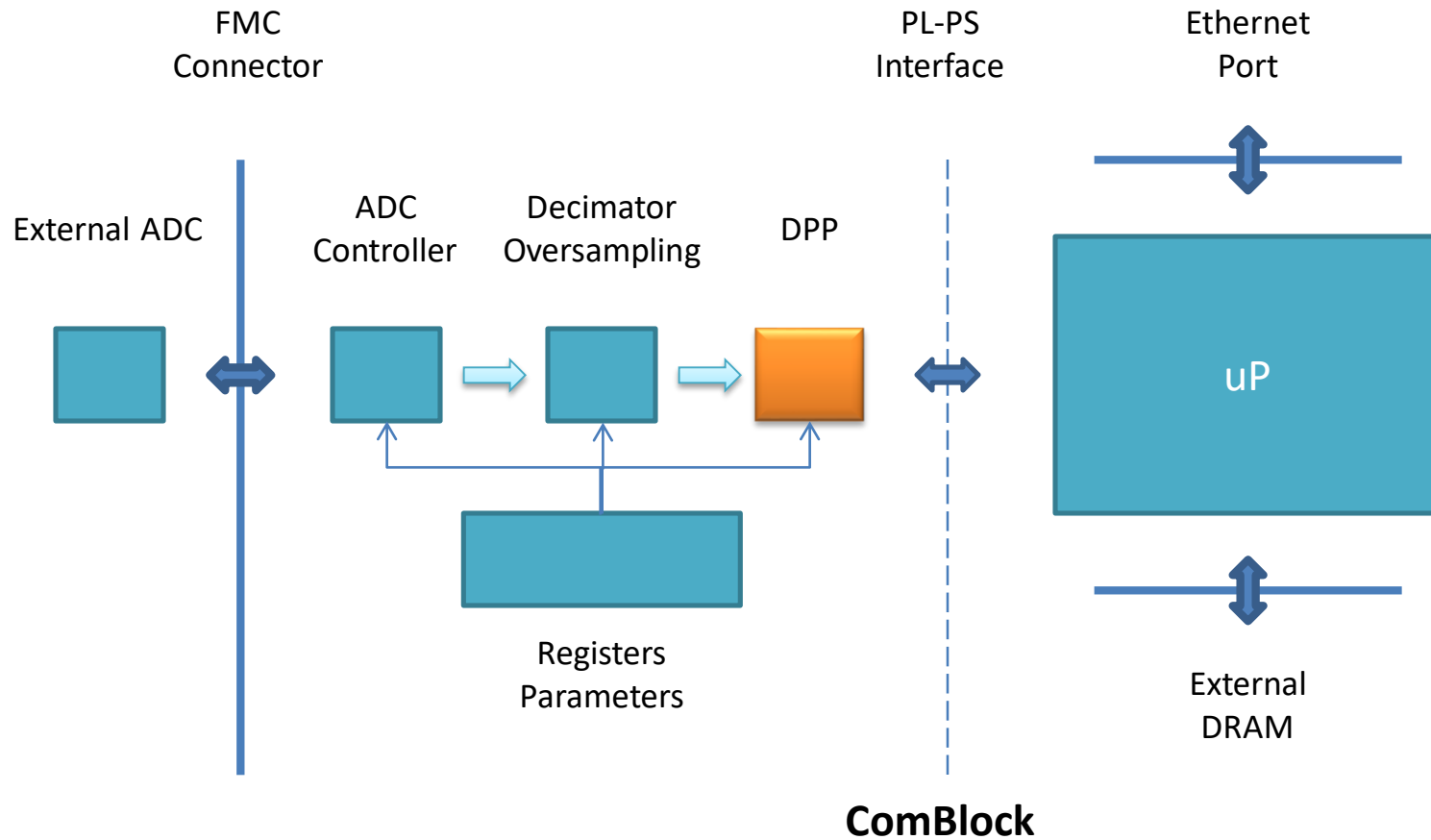
Shaped Pulses



Digital Pulse Processor

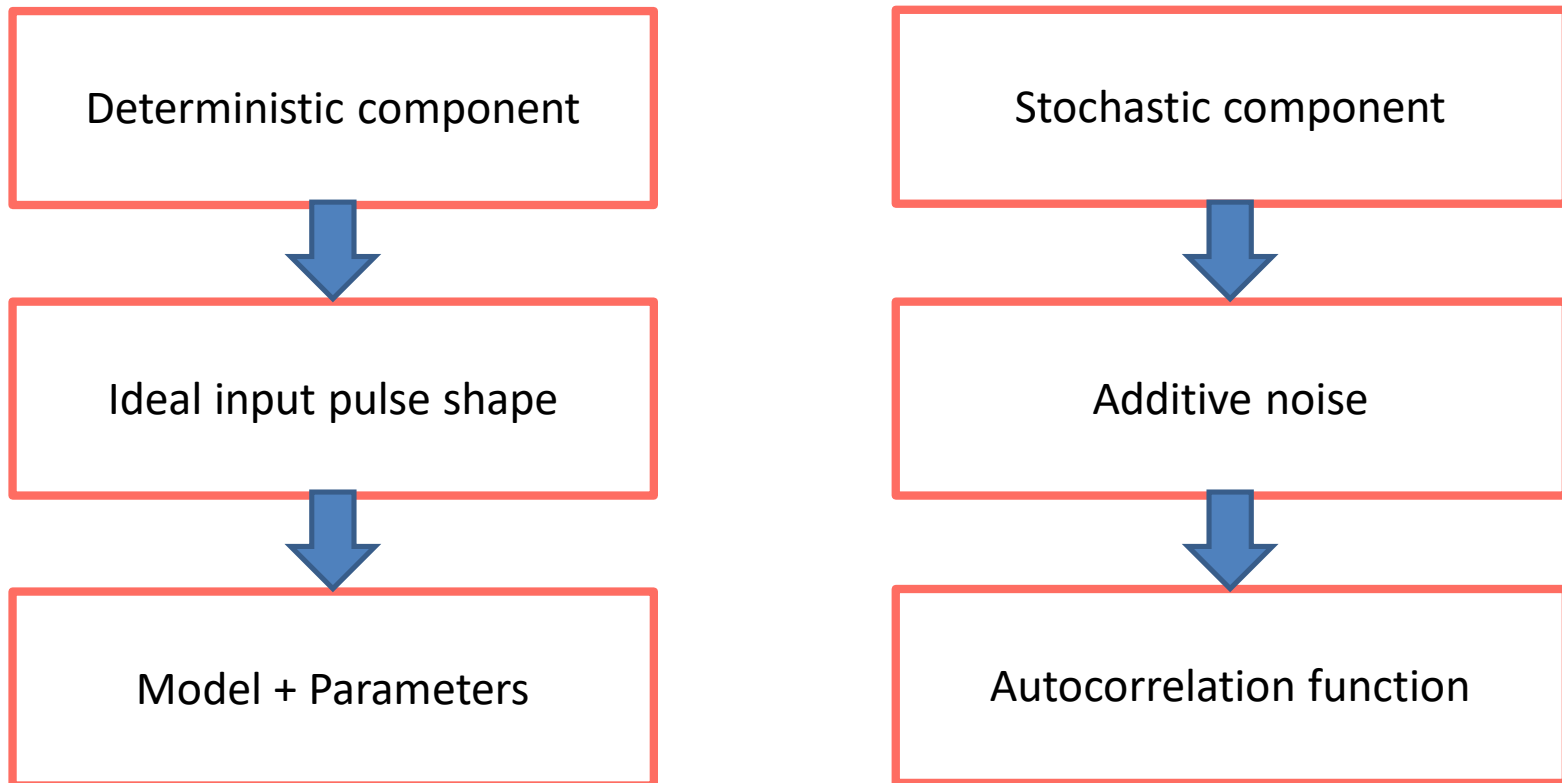


DPP Context in SOC: Global Architecture



FIR Design and Optimization

Input signal analysis



FIR Design and Optimization

Input pulse modeling I

The ideal case corresponding to a single photon detection is represented by the step function S_i

$$S_i = \begin{cases} 0, & i \leq t_0 \\ A, & i > t_0 \end{cases}$$

The finite frequency response of the CSA determines a limited rise time that could be modeled (1st aprox) as an exponential growth

$$S_i = \begin{cases} 0, & i \leq t_0 \\ A(1 - e^{-(i-t_0)/\tau}), & i > t_0 \end{cases}$$

A constant detector leakage current determines a baseline with a steady slope and a variable offset on top of which the signal segment must be processed

$$S_i = \begin{cases} B_0 + iB_1, & i \leq t_0 \\ A(1 - e^{-(i-t_0)/\tau}) + B_0 + iB_1, & i > t_0 \end{cases}$$

Several sources of noise will contribute with an additive spurious signal n_i that degrades the voltage step measurement

$$S_i = \begin{cases} B_0 + iB_1 + n_i, & i \leq t_0 \\ A(1 - e^{-(i-t_0)/\tau}) + B_0 + iB_1 + n_i, & i > t_0 \end{cases}$$

FIR Design and Optimization

Input pulse modeling II

Pile up: Being a Poissonian process, two or more photons could be absorbed in the SDD within any arbitrary small time window. The superposition of two photons absorbed at times t_0 and t_1 and respectively with amplitudes A_0 and A_1 is then given by

$$S_i = \begin{cases} B_0 + iB_1 + n_i, & i \leq t_0 \\ A_0 \left(1 - e^{-(i-t_0)/\tau}\right) + B_0 + iB_1 + n_i, & t_0 < i \leq t_1 \\ A_0 \left(1 - e^{-(i-t_0)/\tau}\right) + A_1 \left(1 - e^{-(i-t_1)/\tau}\right) + B_0 + iB_1 + n_i, & i > t_1 \end{cases}$$

FIR Design and Optimization

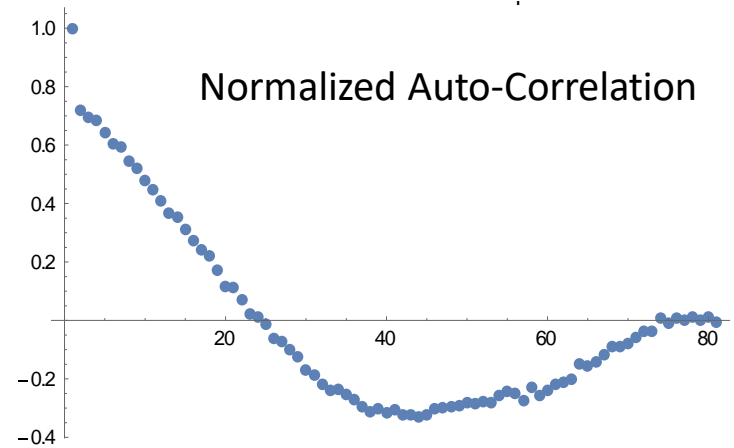
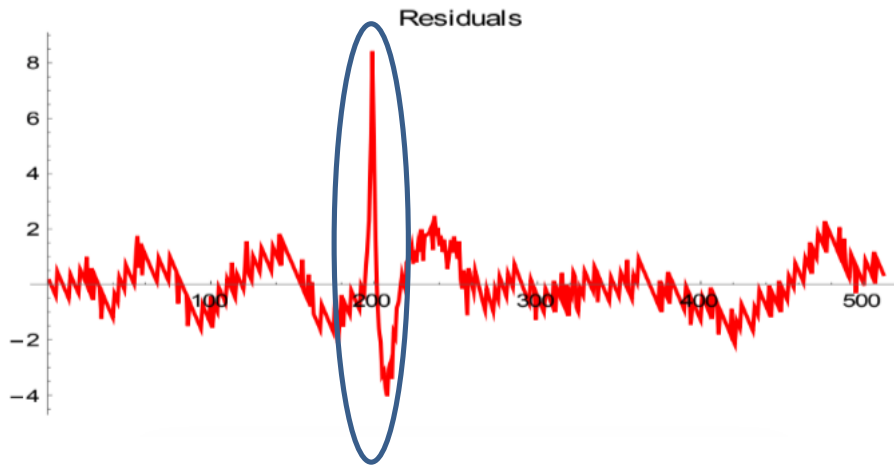
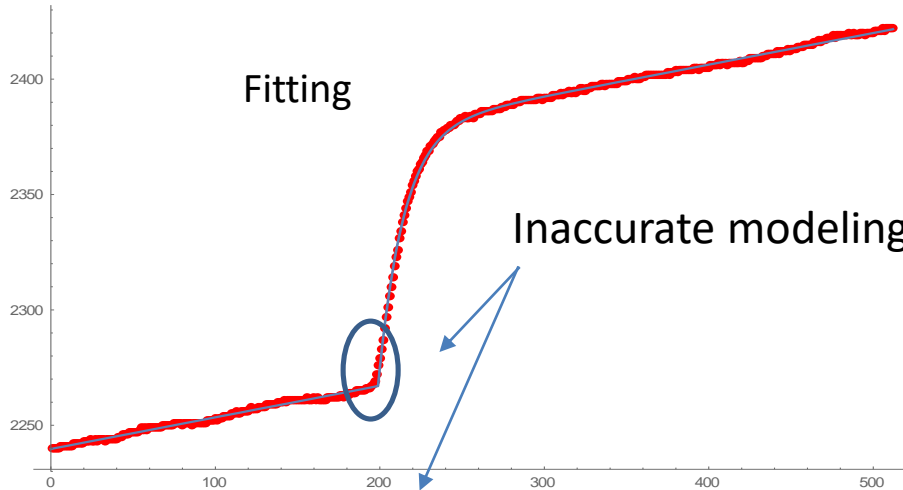
Input pulse modeling III

... and in general for $m+1$ photons

$$S_i = \begin{cases} B_0 + iB_1 + n_i, & i \leq t_0 \\ A_0(1 - e^{-(i-t_0)/\tau}) + B_0 + iB_1 + n_i, & t_0 < i \leq t_1 \\ A_0(1 - e^{-(i-t_0)/\tau}) + A_1(1 - e^{-(i-t_1)/\tau}) + B_0 + iB_1 + n_i, & t_1 < i \leq t_2 \\ \vdots \\ \vdots \\ \sum_{j=0}^m A_j (1 - e^{-(i-t_j)/\tau}) + B_0 + iB_1 + n_i, & i > t_m \end{cases}$$

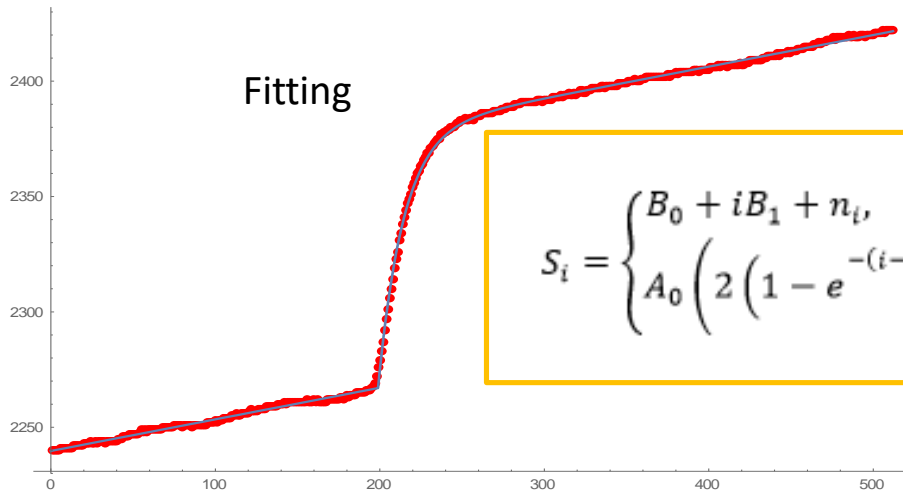
FIR Design and Optimization

Input noise characterization

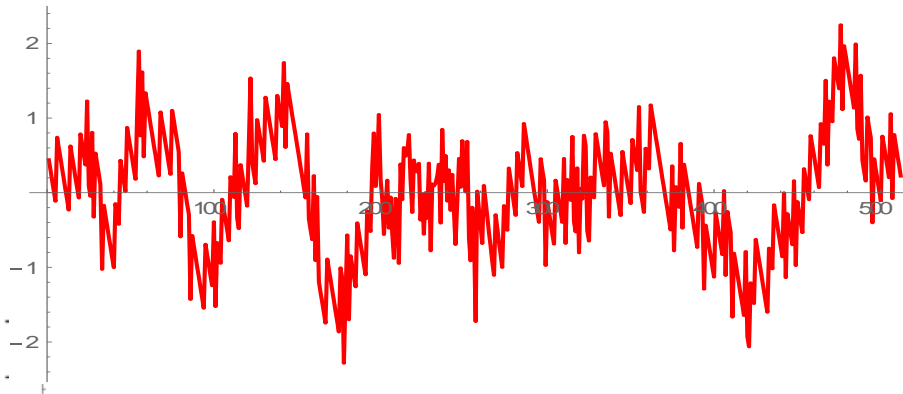


FIR Design and Optimization

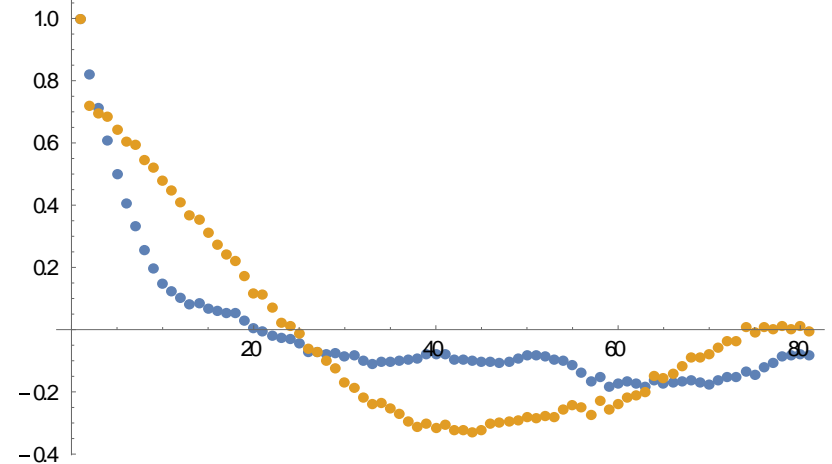
Input noise characterization



Residuals (noise)



Experimental ACF (simple exponential vs bi-exponential fitting)











Summary of main characteristics of a configurable/programmable DPP

- Energy measurement range
- Energy resolution
- Time resolution
- Photon counting
- Dead time measurement
- Pile-up rejection
- Max measurement photon rate
- Max counting photon rate
- Area, performance, power consumption
- Pulse shapes discrimination

More details in

Data Analysis and Filter Optimization for Pulse-Amplitude Measurement: A Case Study on High-Resolution X-ray Spectroscopy

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 Werner Florian Samayoa ^{1,5}  ,  Maria Liz Crespo ^{1,*}  ,  Andres Cicuttin ¹  ,
 Jerome Folla Kamdem ^{1,6}  ,  Luis Guillermo Garcia ^{1,5}   and  Sergio Carrato ⁵  

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A programmable System-on-Chip based digital pulse processing for high resolution X-ray spectroscopy, A. Cicuttin *et al.*, 2016 *International Conference on Advances in Electrical, Electronic and Systems Engineering (ICAEES)*, 2016, pp. 520-525, doi: 10.1109/ICAEES.2016.7888100.