Overcoming the Barrier of High Count-Rate X-ray Analysis
— Real-Time Pile-up Separation and Measurement Technology via Machine Learning

"PurSamurAI (Pile-up Recovery via Smart Algorithm for Multi-pulse Unmixing and Reconstruction AI)"

Until now, we have developed and provided measurement modules compatible with high count rates. However, as the Input Rate increases, the probability of pile-up occurrence rises sharply, the growth of the Net Rate (effective count rate) slows down, and eventually reaches a plateau. With conventional measurement modules alone, this structural challenge was unavoidable.

SamurAI-DSP uses "PurSamurAI (Pile-up Recovery via Smart Algorithm for Multi-pulse Unmixing and Reconstruction AI)," an algorithm independently developed by TechnoAP, to generate highly accurate pile-up separation inference models through machine learning. By inputting overlapping waveforms into this generated inference model, waveforms precisely separated into individual pulses can be obtained.

As a result, it exhibits a remarkable effect not only on improving the Output Rate itself, but even more so on improving the Net Rate. Furthermore, because this separation process is executed in real-time on a PC GPU, high-precision spectra can be acquired while resolving pile-ups on the fly without stopping the measurement. SamurAI-DSP achieves an improvement in effective performance corresponding to the increase in Input Rate under a real-time measurement environment.

The following graph shows the relationship between Output Rate and Input Rate under the conventional Peaking Time setting of 350 ns. At first glance, it appears that the Output Rate rises as the Input Rate increases, suggesting that the useful count improves as the count rate is raised higher.

However, this Output Rate is merely the number processed and output by the detector/measurement module as "some event". Pulses whose energy information is distorted due to pile-up, and pulses where multiple pulses are synthesized and counted in the wrong channel, are treated as the same single count on the Output Rate. In other words, the Output Rate alone cannot determine whether the count of the target energy is actually increasing.

Figure 2 shows the relationship between Net Rate and Input Rate. It can be seen that in the high count-rate region, counts that should originally be obtained continue to be lost due to pile-up. It is only by comparing Figure 1 and Figure 2 side-by-side that this "discrepancy between appearance and reality" becomes clear.

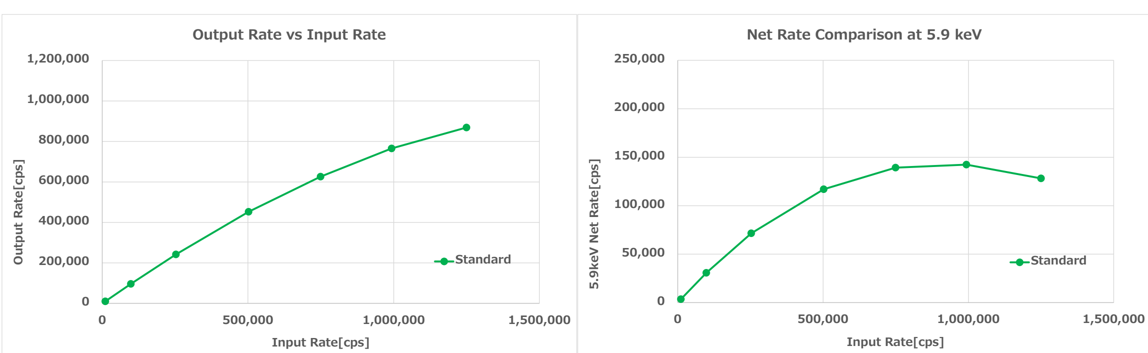

Figure 1: Relationship of Output Rate and Net Count Rate to Input Rate

The arrival intervals of pulses observed by X-ray and gamma-ray detectors are random events following a Poisson distribution. As the count rate r increases, "pile-up," where two or more pulses rush in almost simultaneously within the response time of the detector, occurs at an unavoidable frequency.

If the count rate is r [cps] and the peaking time (risetime + flattop) is τ [s]:

$$\mu = r \cdot \tau$$

$$P_{\text{pileup total}}(r \cdot \tau) = 1 - e^{-\mu} = 1 - e^{-r\tau}$$

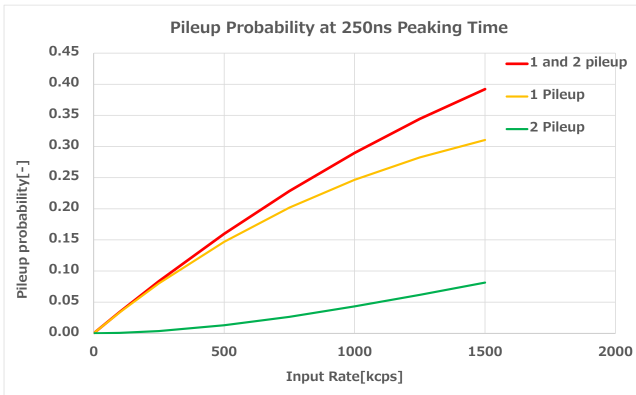

Figure 2: Pile-up Probability

The graph above shows the occurrence probability of 1pileup (two overlapping waveforms) and 2pileup (three overlapping waveforms) as the Input Rate increases. Increasing the Input Rate seemingly continues to increase the Output Rate, but this is only a superficial change.

As shown in the graph, the pile-up probability increases simultaneously with the rise in Input Rate. Pile-up events are "unusable counts" that do not possess correct energy information, and they steadily blend into the increase in Output Rate.

Since the pile-up probability continues to increase along with the rise in Input Rate, the loss due to pile-up comes to exceed the increase in Input Rate. **The result where the Net Rate plateaus and eventually turns to a decrease as the Input Rate is raised further is similarly supported by this pile-up probability graph.**

As described, pile-up, which always occurs at high count rates, increases at an unavoidable frequency along with the count rate as indicated by Poisson statistics. With conventional pile-up rejection (PUR), there was no choice but to discard the entire waveform.

SamurAI-DSP addressed this challenge by constructing a dedicated model to separate pile-up waveforms into individual pulses through machine learning.

The following is a brief introduction from machine learning to measurement.

1.Measurement Preparation

Connect the detector and set the measurement parameters.
Input an arbitrary signal and start one-click machine learning.

2.One-Click Machine Learning and AI Build

By executing "One-Click Machine Learning," the processes from model training by the following machine learning steps ① to ③ through to building the inference engine (executable file) are automatically executed.

① Acquisition of raw trapezoid-shaped waveforms for training

The training uses actual "single-shot waveforms" that include the characteristics of the detector, noise, and the surrounding environment, rather than ideal waveform function models or waveforms without noise.

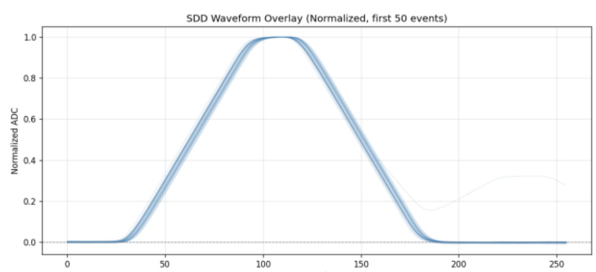

Figure 3. Acquisition of waveforms for teacher data

② Generation of training data and machine learning

Using the single-shot waveforms acquired in ①, machine learning is started by the PurSamurAI engine.

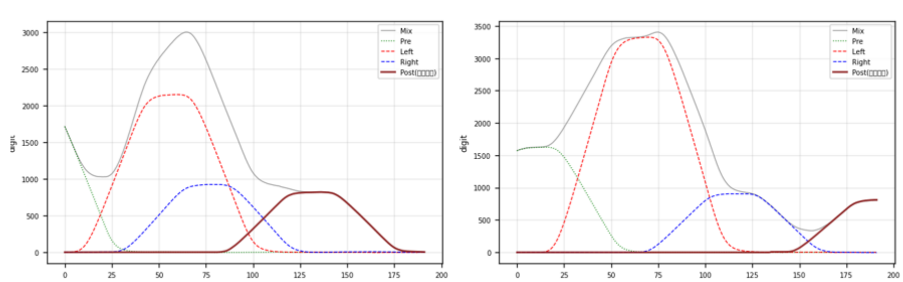

Figure 4. Generation of data for machine learning

3.Measurement

③ Conversion to the inference engine

The trained model is converted into an inference engine optimized for the installed GPU and automatically set in the application to be used.

Start the measurement. At startup, the inference engine is deployed to the GPU.

During measurement, pile-up waveforms are instantaneously acquired through high-speed 10G Ethernet transmission and inferred and separated in real time on the GPU.

In GPU inference, the root mean square error (RMS) is automatically calculated to determine whether to accept or exclude the waveform. The result is then plotted as a spectrum.

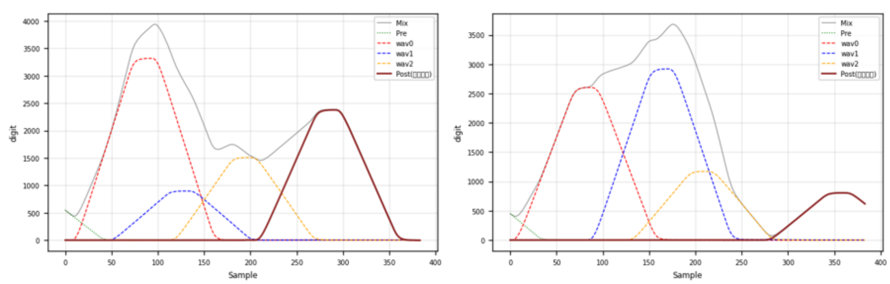

Figure 5. Example of an actual raw waveform separated by SamurAI-DSP

4.Repeated measurement

The constructed inference engine can be reused when the same measurement parameters are used. If the parameters are changed, measurement can be started by switching to a dedicated engine according to the conditions.

Actual measurement data is shown below. This is a comparison of Output Rate and Net Rate against the Input Rate shown earlier.

It can be seen that the Output Rate, which is the conventional evaluation standard, is improved by 115%, and particularly the Net Rate, which is originally required, has its count rate improved by as much as 166% in the 1 Mcps Input Rate region.

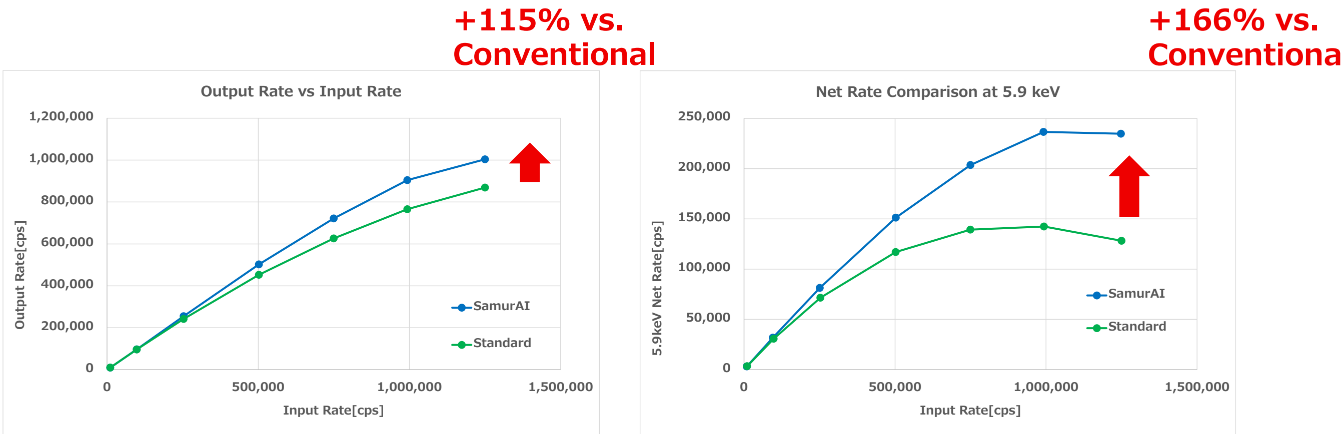

Figure 6: Comparison of Output Rate and Net Rate between Conventional Method and SamurAI-DSP

This is a comparison of Energy Resolution against Input Rate.

It was demonstrated that SamurAI-DSP maintains energy resolution compared to the conventional method, despite separating pile-ups.

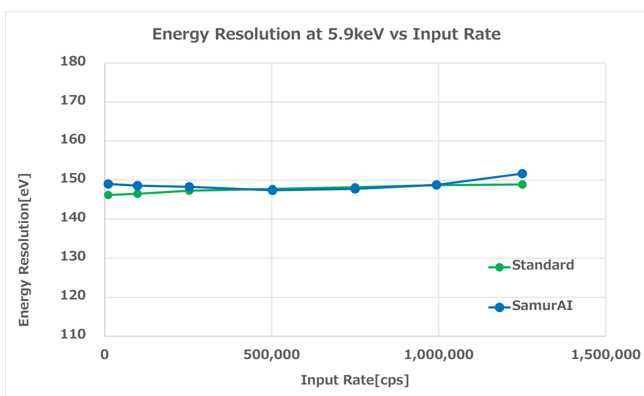

Figure 7: Energy Resolution and Input Rate

The overall spectrum at 1M Input Rate is shown. Black represents the Standard setting, and blue represents the SamurAI-DSP spectrum. An increase in the peak around 5.9 keV and a decrease in the background on the high-energy side can be observed.

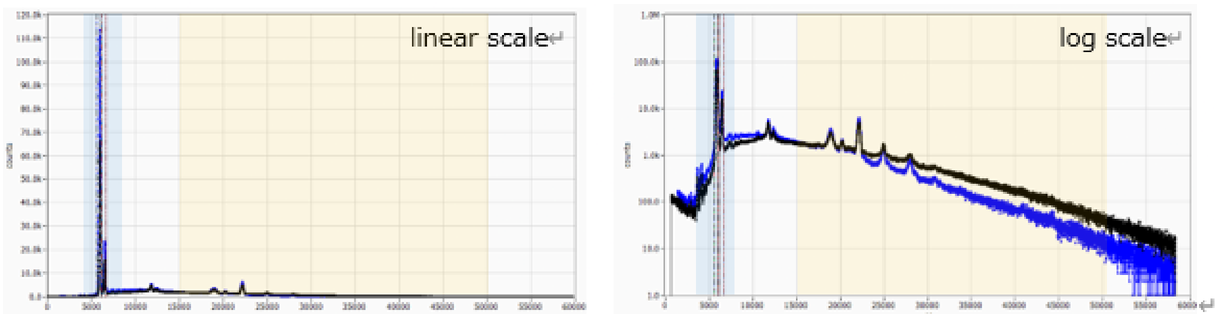

Figure 8: Comparison of Overall Spectrum between Conventional Method and SamurAI-DSP

This is an enlarged view of the spectrum around the 5.9 keV and 6.4 keV peaks, as well as on the high-energy side. By applying SamurAI-DSP, while the Net Rate at the 5.9 keV and 6.4 keV peaks is significantly improved, a remarkable reduction in background is confirmed in the high-energy region of 15 keV and above. This indicates that signals conventionally miscounted on the high-energy side due to pile-up were precisely separated through multi-pulse separation and reconstruction processing, and reconstructed into their original energy peaks.

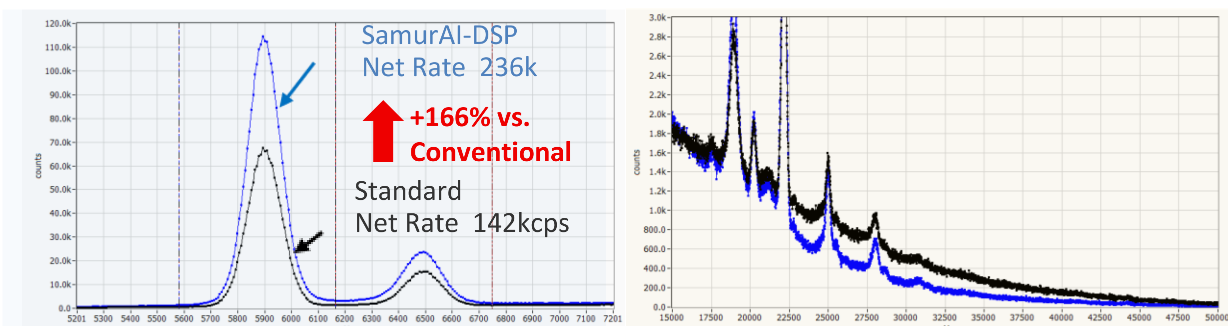

Figure 9: Comparison of Enlarged Spectrum between Conventional Method and SamurAI-DSP

This figure shows the real-time Pileup Rate and Separate Rate achieved by SamurAI-DSP during measurements at an input rate of 1 Mcps. Pileup waveforms above 200 kcps are processed in real time, achieving a separation rate of up to 345 kcps. With high-speed inference using a GPU, the system outputs not only separated waveforms and pulse heights, but also information such as the number of successful and failed separations.

	count	rate(cps)
reject after hist	**5.588M**	**558.828k**
pileup	**2.056M**	**205.613k**
Separate	**3.453M**	**345.337k**

Number of detected pileups and transferred waveforms

Number of separated events by SamurAI-DSP

Figure10: pile-up processes during measurement

SamurAI-DSP has succeeded in recovering pile-up events, which were completely discarded in conventional pile-up rejection, with a practical resolution.

By combining waveform separation through machine learning with GPU real-time processing, the "truly usable count rate (Net Rate)," which is lost as the count rate increases, is recovered, fundamentally raising the analytical performance in high count-rate environments.

The true nature of this sluggish growth in Net Rate is the very increase in events that are either "discarded" or "used while remaining distorted" due to pile-up. In other words, if individual pulse information can be precisely recovered from pile-up waveforms, the Net Rate that would have been lost until now can be reclaimed, allowing effective counts to continue extending in a more linear fashion relative to the rise in Input Rate.

What was standing in the way was not the limit of the detector, but the "processing barrier."

SamurAI-DSP guides measurement beyond that limit.