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A robust digital signal processor: Determining the true input rate

T. Papp [a,b,*], J.A. Maxwell [a]

[a] Cambridge Scientific, 175 Elizabeth Street, Guelph, ON, Canada N1E 2X5
[b] Institute of Nuclear Research of the Hungarian Academy of Sciences Bem ter 18/c Debrecen, H-4021, Hungary

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ABSTRACT

In addition to proper spectral deconvolution, accurate quantitative work in energy dispersive X-ray or gamma-ray spectrometry requires information about the number of particles striking the detector in a given measurement time. This requires knowledge of the analysis system dead time as well as events lost from the spectrum due to pileup and event discrimination. This is particularly true at high input rates where the correction factors can be significant. In any system where noise is present and is capable of triggering the detection electronics or algorithm it is not sufficient to simply "count" the triggering events and use assumptions about the distribution of arrival times to make pileup loss corrections in order to determine the incident rate of X or gamma rays on the detector. It is necessary to understand the nature of the rejected events and their spectral distribution. The Cambridge Scientific CSX series of digital signal processors provides a separate spectrum of rejected events in addition to the normal spectrum that allows a more accurate determination of the real event input rate, providing a greater level of quality assurance in the measurement. A method for determining the true input rate is presented and examples are given where the rejected spectra are dominated by noise, noise–event pileup, event–event pileup, single event rejection and unrelated but real event rejections.

1. Introduction

Quantitative work in energy dispersive X-ray (or gamma ray) spectroscopy (EDXS) requires knowledge of the true input rate impinging on the detector. This along with the analysis of the acquired spectrum provides the basis for quantitative elemental analysis using such techniques as energy dispersive X-ray fluorescence analysis (EDXRFA), particle induced X-ray emission (PIXE) and particle induced gamma-ray emission (PIGE).

For example, a typical EDXRFA system will consist of an X-ray source, a sample holder or chamber, a solid state detector such as Si(Li) (lithium drifted silicon detector) or a silicon drift detector (SDD) or pin diode, and a detector electronics package that converts the interaction signal from the detector into an energy spectrum of events for analysis. However, in order to produce a relatively clean and well-resolved spectrum of events, the signal processing system requires a finite processing time that introduces dead periods where events may be missed altogether as well as rejecting many detected events that appear distorted, excessively noisy or that are piled up with other events within the processing interval. Other losses of sample X-rays occur due to non-interaction in the detector volume for any number of reasons but here we will concentrate on the electronic loss component.

In order to correct the observed elemental peak areas for lost events the analyst must use the true event input rate along with the observed spectral output rate to estimate the actual number of X-rays of that element striking the detector, which in turn will be used to estimate the elemental concentrations. At very low input rates the output rates can be equal to or at least linearly proportional to the input in a constant or low noise environment. However as the input rates increase, the fraction of electronically lost events increases and in noisy environments the fraction of lost events can vary with the noise. With the rapid deployment of such instruments to industrial settings with their requirements for fast yet accurate measurements, necessitating the use of high input rates in variable noise environments, a robust method for determining the true X-ray input rate of a measurement is required [1].

Many papers have been written on dead-time losses and pileup corrections and the methods used to compensate for each and a general discussion of the problems can be found in Knoll [1]. Typically it is assumed that there is a dead time associated with each detected event and that this is the minimum separation time between events to be recorded as separate events in the spectrum [1]. Knoll goes on to define models for dead time based on paralyzable and nonparalyzable systems with real measuring systems usually falling somewhere in between these two extremes of behavior. He further suggests that one should

* Corresponding author at: Cambridge Scientific, 175 Elizabeth Street, Guelph, ON, Canada N1E 2X5. Tel.: +1 519 780 1760; fax: +1 519 780 0218.
E-mail address: tibpapp@yahoo.ca (T. Papp).

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attempt to work at low loss rates as losses exceeding 30–40% will result in calculated input rates being very sensitive to small changes in the measured rate. These models are for multiple-event pileups but do not take into account any single event rejection to improve spectral quality.

Thus, the ability to perform accurate measurements in a reasonable time will depend on a trade off between several factors. The statistical accuracy will depend on the number of resolved counts in the X-ray peaks which in turn will depend on the time of measurement, resolution of measurement (which is usually dependent on the processing time) and the true event input rate. Statham discusses this nicely in [2]. Corrections to the peak areas will depend on losses due to the system dead time, the discrimination of events and the measured or calculated true event input rate. Errors in the overall estimation of the number of events will result from deconvolution or fitting errors, statistical accuracy and the errors in the correction factor applied to the peak areas.

Below, we present how the use of a robust digital signal processor can reduce the error in the correction for electronic losses through examination of the rejected event spectrum.

A discussion of some of the earlier attempts at digital pulse processing for X-ray spectra can be found in Ref. [3].

2. Observations and measurements

2.1. The CSX pulse processor

Cambridge Scientific, Canada [4] produces a line of digital signal processors, the CSX series, whose main distinction is that it simultaneously produces a spectrum of the accepted events that pass the various discrimination tests as well as a spectrum of the rejected events that failed one or more of the tests.

The CSX processors digitize the active reset preamplifier signal and then digitally analyze this train to obtain the spectra. Details of the CSX units and observations of various characteristics such as line shape, throughput rate, resolution vs. input rate and processing time can be found in Refs. [4–9]. Here we will concentrate on using our knowledge of the dead time and the rejected spectrum feature to better determine the true event input rate.

2.2. Dead time correction

There are generally two sources of dead time in solid state detector systems; the preamplifier dead time associated with its resets and the processing dead time associated with the pulse processing electronics or algorithm. The CSX units count the preamplifier resets and additionally provide an oscilloscope mode that allows the analyst to determine the reset dead time if that information is not available from the manufacturer.

In the CSX units the processor dead time is defined as that time in which the algorithm is either not actively looking for the next event or in the middle of processing an event that will appear in the accepted or rejected spectrum. This is the only time that an event edge can occur and not either be seen or result in information about that event being recorded in one of the spectra. Depending on the model and mode of operation, this is usually a few hundred nanoseconds per processed event. Essentially the CSX units are *mixed paralyzable* processors.

In a nonparalyzable system there is a fixed length dead time associated with each processed event. Any additional pulses that occur within that time are ignored but do not extend the dead time. This results in an observed count rate that increases asymptotically with the real event rate to a rate equal to the inverse of the dead time. In a paralyzable system the dead time associated with each event can be extended by subsequent events that occur within that time. This results in an observed count rate that increases as the real input rate increases up to a rate equal to the inverse of the dead time and thereafter decreases towards zero as the real input rate increases—thus the nomemclature *paralyzable*[1].

The accepted spectrum is a paralyzable system with its counting rate increasing with increasing input rates up to some maximum (depending on the signal processing time) and thereafter decreasing as the real input rate increases. However, almost all of these lost events from the accepted event spectrum will appear in the rejected event spectrum in the form of pileups that allows a calculation of the true event input rate. The rejected spectrum is totally nonparalyzable although events in this spectrum can represent 0 (noise only), 1, 2 or more X-ray events. By the nature of the pulse processing in these units, where a time interval before the edge as well as an interval after the edge is analyzed for each recognized event, the dead time actually decreases when the input rate increases as the dead time after one event's processing can be captured in the pre-step time of the next recognized event and thus will be captured within that event's processing time. If the assumption of Poisson statistics is valid then the decrease in dead time can be explicitly calculated for any given input rate and pulse processing time. If deemed necessary the CSX units have a mode that provides an interval time histogram for checking this assumption.

Thus for the CSX units the system dead time, for any given measurement, is given by the number of resets of the preamplifier multiplied by the reset dead time plus the number of processed events multiplied by the processor dead time.

Using this definition of dead time, the dead time correction in the CSX units is generally small for realistic input rates. However, the pileup correction factor, which is sometimes included in the dead time for other processors, can increase rapidly as the average time interval between input events decreases (input rate increases) towards the pulse processing time.

2.3. Pile up correction

Event pileups can be seen in both the accepted and rejected spectra. For those events that occur close enough together in time that the discriminators are not triggered then these events will appear in the accepted spectrum usually as true pileup or sum peaks with energies equal to the sum of the energies of the underlying events. Events with time separation great enough to be discriminated against but less than the pulse processing time will appear in the rejected spectrum with energy between that of the first triggered event and the sum of the first and subsequent events whose edges appear in the processing interval of the first event.

Often people will attempt to do a pileup correction calculation based on the observed pileup peaks in their spectrum but this does not properly take into account the rejected pileup events that usually have a much different pileup resolving time. As these events are not normally seen, the analyst has to rely on the reported input rate, dead time and specific knowledge or assumptions about the processor to estimate this loss.

With the CSX processors one can process the rejected spectrum to obtain the actual number of X-rays removed from the accepted spectrum. In many cases a simple recipe can be used to estimate the average number of X-rays per rejected spectrum event and thus a pileup correction factor. We outline such a procedure below.