# A robust digital signal processor: determining the true input rate

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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.

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## 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 XRF, PIXE and PIGE.

For example, a typical EDXRFA (Energy Dispersive X-Ray Fluorescence Analysis) system will consist of an x-ray source, a sample holder or chamber, a solid state detector (Si(Li), SDD, 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 requiring high input rates in potentially highly varying noise environments a robust method for determining the true x-ray input rates for measurements is required.

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 attempt to work at low loss rates as losses exceeding 30 to 40% will result in calculated input rates being very sensitive to small changes in the measured rate.

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 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 reference [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 the following references [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 the 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 not actively looking for the next event or in the middle of processing an event that will appear in either 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 less than 1 microsecond per processed event. Essentially the CSX units are *mixed paralyzable* processors. The accepted spectrum is a paralyzable system with its counting rate increasing with input rate 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 show up in the rejected event spectrum in the form of recognized pileup which 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.

The dead time for any given measurement is thus given by the number of resets 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, that 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 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 had 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.

In figure 1, we show a monochromatic Cu Kα1 spectrum. Although this is a very simple spectrum it can be used to demonstrate the proper use of information from the rejected spectrum.

Below 1 keV we see a noise peak. These events represent noise and noise piled up with noise so they essentially include no real x-ray events. From this region up to the end of the Cu Kα1 peak we have a spectrum of single x-ray events (either alone or as noise triggered pile up events). From the peak to the sum peak (at 16 keV) we see a region dominated by Cu Kα1 x-rays piled up with one another - 2 x-rays in this region and 3 x-rays above the sum peak. Note that there will be a small contribution of 3 event pile up (as designated by the dotted line) in the region between the CuKα1 peak and its sum peak. So in this case it is relatively easy to determine the number of x-rays lost from the accepted spectrum but contained in the rejected spectrum. One can sum the counts in the various regions and assign either 0, 1, 2, 3 or more x-rays as appropriate.

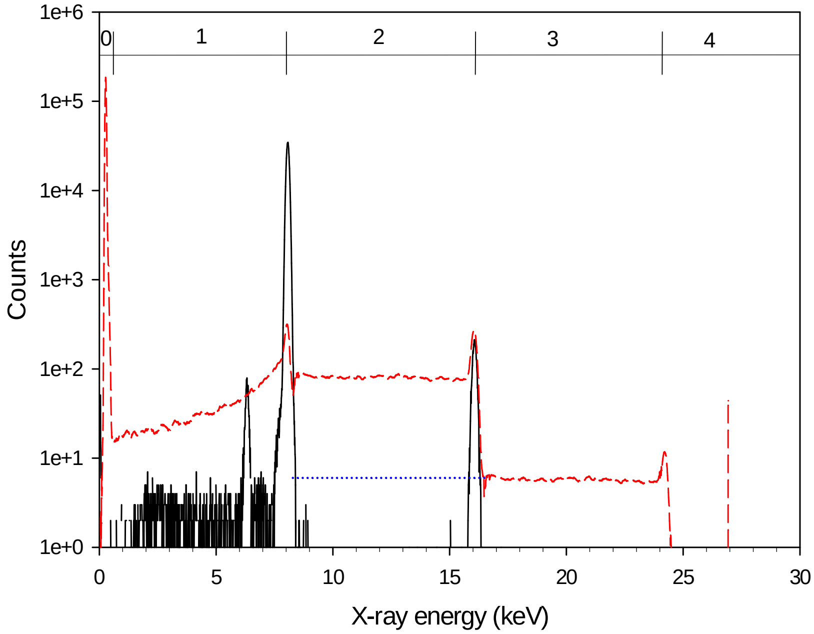


Figure 1. The x-ray spectrum of Cu Kα1 line from an x-ray monochromator, measured with a Si(Li) detector and a CSX4 digital signal processor. The processor separates the events to desirable and non-desirable events. The rejected (non-desirable) events spectrum is presented with a dashed line. The settings of the parameters of the measurements were selected for the purpose of explanation, namely the signal recognition was set to a low level to allow the presence of the noise peak in the rejected spectrum.

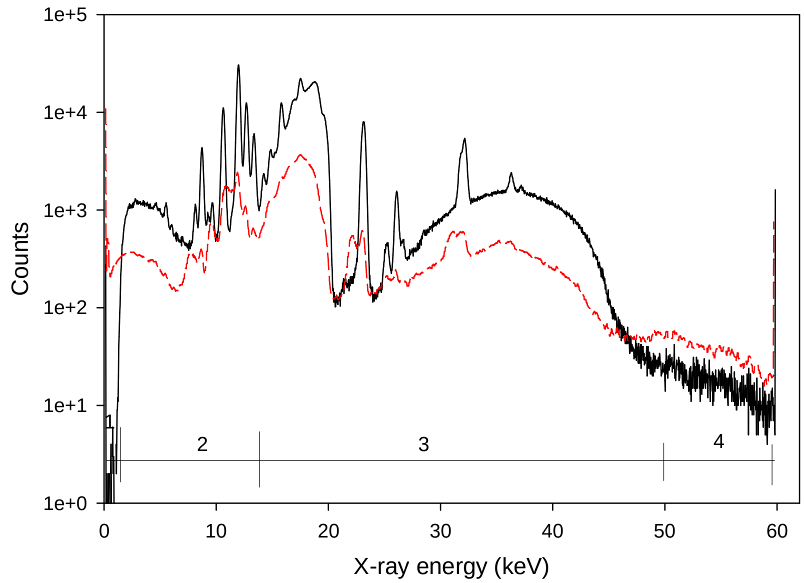


Figure 2. An XRF spectrum of a PVC sample measured on a portable XRFA device. The rejected spectrum is also shown with dashed line. The four regions indicated represent a division of the rejected spectra into regions where each event represents 0, 1, 1 or more, 2 or more real x-rays. That is 1) pure noise, 2) a single x-ray event along with pileup with noise, 3) a region of combined single event and pileup of two or more x-rays, 4) pileup of two or more x-rays.

In figure 2 we show a more usual analytical spectrum along with its rejected event spectrum. This is the spectrum of a PVC standard, measured at 50 kV x-ray tube voltage using a Mo pre-filter on a portable XRFA device. In most measurements the rejected spectrum can be divided into three or four regions, one region right at the beginning of the spectrum possibly dominated by noise and noise + noise pileup (<1keV ), the next region dominated by rejected single x-ray events or single x-ray events piled up with noise (region 2), a third region where pileup of x-rays with other x-rays mixes with rejected single x-rays (possibly piled up with noise as in the $2^{nd}$ region) and possibly a fourth region, present in this case as indicated by region 4, of purely piled up x-ray events. The second region essentially provides a base of rejected single x-ray events that can be scaled to the identical region in the accepted spectrum. This ratio can be used to determine the number of rejected events that represent single rejected x-rays with the remaining events (in regions 3 and 4) representing two or more x-rays. The assumption that is made here, that is a real problem with many systems, is that the single event rejection rate is essentially energy independent. Here, this assumption is readily checked by comparing the amplitudes of rejected peaks with the amplitudes of the identical accepted peaks over a range of energies. The average number of x-rays per pileup event can be estimated by iteration using the calculated x-ray input rate and the pulse processing time and the assumption of Poisson statistics. The x-ray input rate is then calculated as the single events in the accepted spectrum + the pileup events in the accepted spectrum multiplied by the average number of x-rays per pile up in the accepted spectrum + the single x-ray events in the rejected spectrum + the piled up x-rays in the rejected spectrum multiplied by the average number of x-rays per pileup event in the rejected spectrum + the number of resets all divided by the live time (measure time - dead time). Two items of note are that the purely noise events are ignored and this is an important point and provides another reason for examination of the rejected events and further, the assumption is made that a reset was probably triggered by a real event that was then lost from both spectra. The average number of x-rays per accepted event pileup can be readily calculated from analysis of the true pileup peaks in the accepted spectrum. The average number of x-rays per pure x-ray pileup in the rejected spectrum can initially be assumed to be the same as that in the accepted spectrum to find the first estimate of the input rate. This input rate can be used along with the pulse processing time to estimate the number of x-rays per rejected spectrum pileup event. This procedure is iterated until the input rate is essentially unchanging.

With a measure of both the single x-ray event accepted counts and the calculated overall x-rays detected in the live time, a correction to the characteristic line counts for pileup, single event rejection and dead time is readily obtained. Corrections for detector efficiency effects will then yield the number of characteristic x-rays impinging on the front of the detector in the measuring time. Further corrections for x-ray absorbers between the sample and the detector will give the number of x-rays leaving the sample in the direction of the detector.

There is one important caveat. The analyst needs to be aware and take warning that when the corrections become so large as to be a significant fraction or even larger than the observed counts then there is a potential for a large associated error. This is one reason that high count rates with the attending large corrections have been so unreliable in the past. Low error corrections depend highly on accurate estimates of the true single event x-ray rate and thus analysts were forced to work at lower input rates where corrections are less significant for more accurate measurements or accept larger errors in their measurements. The CSX processors, with analysis of the rejected spectrum events, greatly reduce the errors in determining the rate dependent and pulse rejection factors (noise, pileup, single event rejections and dead time) in the true x-ray input rate making analytical work at higher counting rates subject to less error.

## 2.4 Further Observations

Below we present some further observations of how the implied input rate is affected by the observations of the rejected spectrum in conjunction with the accepted event spectrum.

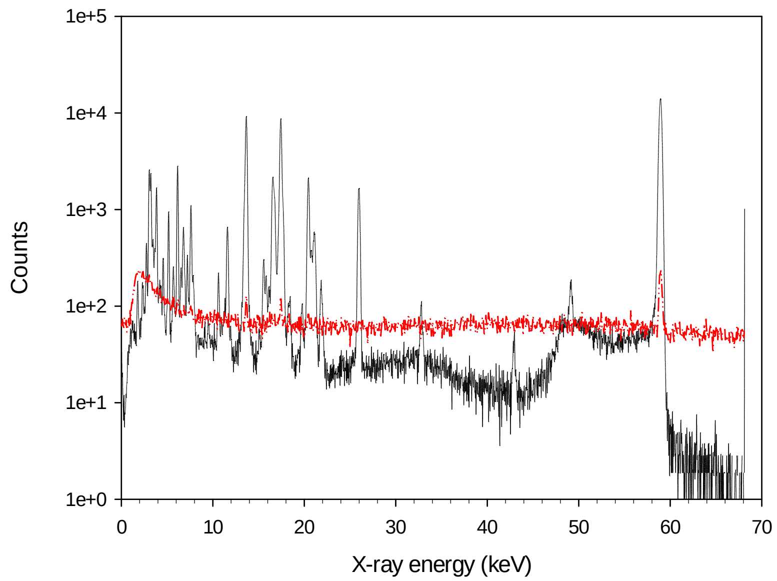


Figure 3. An $^{241}$Am spectrum measured with a HPGe detector and a CSX4 signal processor. The accepted spectrum is drawn by a continuous line and the rejected spectrum with a dashed line.

The input rate was about 50 counts per second. Therefore event-event pileup peaks are not expected, and are not visible. There are small peaks in the rejected spectrum, coinciding with peaks in the accepted spectrum, that represent single event rejections however the majority of rejected events are unrelated to the x-ray spectrum and are likely due to energetic particles or scattered high energy events.

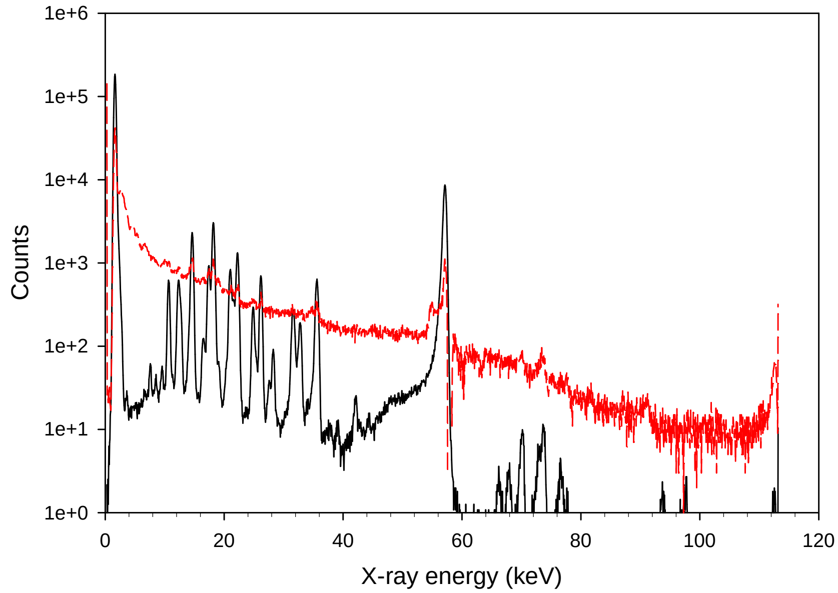


Figure 4. An $^{241}$Am spectrum measured with a CdTe PIN diode detector.

Here the rejected spectrum (dashed line) is dominated by noise and noise triggered real events. If the signal recognition level were set higher, and the low energy potential signals were not initiating an event processing, the noise triggered events would be much smaller in size.

Figure 3 shows an $^{241}$Am spectrum measured with a HPGe detector and a CSX4 signal processor. The input rate was small so no event-event pileup is expected. However, without the rejected event spectrum the lost events might be assumed to be due to single event rejections, or noise-triggered pileups of single real events, leading the analyst to estimate too large an input rate. There are small peaks in the rejected spectrum, coinciding with peaks in the accepted spectrum, that represent single event rejections, however the majority of rejected events are unrelated to the x-ray spectrum and are likely due to energetic particles or scattered high energy events. As such they should not be included in the real event x-ray rate.

Figure 4 shows an $^{241}$Am spectrum measured with a CdTe PIN diode detector and a CSX4 processor. Here the first 60 keV of the rejected spectrum is dominated by noise and noise triggered real events. The last part is dominated by noise-triggered pileup with two events. If the signal recognition level were set higher, and the low energy potential signals were not initiating an event processing, the number of noise-triggered events would be greatly reduced. The rejected spectrum should be analyzed as a low energy noise peak followed by a majority of noise triggered single x-ray events up to 60 keV (there will be a small fraction of noise triggered double x-ray events underlying this majority of single events just as indicated in figure 1) and then noise triggered double x-ray events beyond that point.

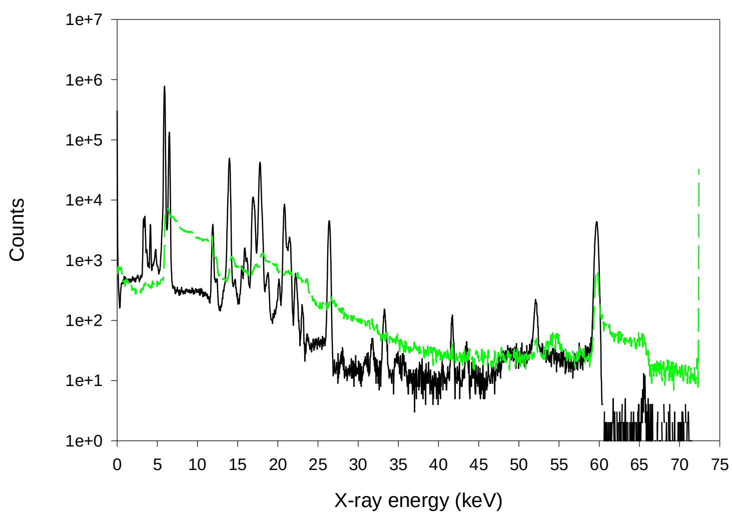


Figure 5. A combined source of $^{55}$Fe (Mn K lines) and $^{241}$Am spectra is measured with a Si(Li) detector and a CSX3 processor. The rejected spectrum shows the event-event pileups as an upper energy side plateau. The intensity of the Fe source was much higher, therefore the Am lines pile up with the Mn lines to dominate the pile up structure. Nevertheless the rejected spectrum has all the noise, noise and event pileup, true pileup, e.g. event and event pileup. The rejected spectrum combined with the accepted spectrum allows one out the various components and thus determine the true input rate.

Figure 5 shows the combined spectra of an $^{55}$Fe and $^{241}$Am as measured with a Si(Li) detector and a CSX3 processor. The rejected spectrum shows the event-event pileups as an upper energy side plateau. The intensity of the Fe source was much higher, therefore the main pileup features we see are the 6 keV plateaus that follow each line in the spectrum. There will be lower plateaus extending from each peak (plus 6 keV) down to the Mn K lines for pileup events that were first triggered by the higher energy events. In this case we would conclude from the rejected spectrum that it consists primarily of x-ray to x-ray pileup so that above 6 keV each rejected event is essentially the combination of 2 x-rays. However, there is one additional noteworthy feature. The lack of peaks in the rejected spectrum coinciding with the peaks of the accepted spectrum would indicate that there is little single event rejection in these regions. For the 60 keV gamma line however we see a significant single event rejection peak. This indicates that there is an energy dependent electronic efficiency for collecting events in the accepted spectrum. Without this knowledge the analyst could easily obtain the wrong ratio of gamma events to L x-ray events in this spectrum.

3. Summary & Discussion

In order to obtain reliable quantitative information about a measurement the analyst needs to be able to deduce the real event x-ray (or gamma ray) input rate in order to apply the appropriate rate dependent corrections to the normally observed (accepted event) spectrum. In order to deduce the real input rate a dead time correction must be applied in order to obtain the live-time to real-time correction factor. Traditionally the dead time correction would include some correction factor for events lost to pileups but this usually depended on several assumptions that could not be readily verified.

The CSX digital signal processors from Cambridge Scientific provide an exact method for determining the actual system dead time based on the number of processed events and preamplifier resets. Also, in addition to the normal accepted event spectrum a spectrum of the rejected events is also provided. This provides the analyst with the ability to observe the rejected events and thus allows the development of algorithms for determining the number of lost real events. The rejected events will include noise events, noise piled up with noise and real events, single-event rejection peaks for those individual events that do not pass the event discrimination tests, multiple-event pileups as well as non x-ray (particle or high energy) events that generate a signal in the spectrum.

Inspection of the rejected spectrum is important for determining the noise contributions to the reported count rate as well as readily indicating when there is an energy dependent electronic efficiency to be taken into account, e.g. see figure 5.

As we have seen from the spectra presented above it is often not sufficient to have the accepted spectrum and an input rate counter value. The circumstances for each spectrum collected can be quite different, depending on the source of the radiation, the environmental noise and the settings of the signal processors.

For example, radioactive sources will often have a component in the spectrum that is unrelated to the x-rays of interest that may be rejected at a different rate than the x-rays themselves - see figure 3 above. Thus it is not sufficient to see the accepted spectrum and know what percentage of events have been rejected, it is necessary to see the rejected spectrum to know what “kinds” of events have been rejected.

The Cambridge Scientific energy dispersive x-ray signal processors (CSX units) provide a robust way to determine the fraction of single x-ray events lost from the analytical spectrum due to noise, rejected events and pileup. This allows analysis software the opportunity to correct for the losses and determine the *corrected* principal line intensities for each element of interest in the spectrum.

What we would suggest is that when an analyst is setting up to do a series of quantitative measurements; that a representative measurement needs to be performed, the rejected spectrum analyzed and a suitable algorithm developed to determine the number of lost real events. At a minimum, the rejected spectrum needs to be monitored on a regular basis in order to provide assurance that the measurement circumstances have not changed.

Thus we conclude that analysis of the rejected spectrum provides an added level of quality assurance that is important for quantitative measurements especially in noisy environments or in cases where the count rate is high and the corrections for losses due to dead time and pileup are significant.

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