The use of energy windowing to discriminate SNM from NORM in radiation portal monitors

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Abstract

Energy windowing is an algorithmic alarm method that can be applied to plastic scintillator-based radiation portal monitor (RPM) systems to improve operational sensitivity to certain threat sources while reducing the alarm rates from naturally occurring radioactive material. Various implementations of energy windowing have been tested and documented by industry and at Pacific Northwest National Laboratory, and are available in commercial RPMs built by several manufacturers. Moreover, energy windowing is being used in many deployed RPMs to reduce nuisance alarms and improve operational sensitivity during the screening of cargo. This paper describes energy windowing algorithms and demonstrates how these algorithms succeed when applied to "controlled" experimental measurements and "real world" vehicle traffic data.

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1. Introduction

Following the events of September 11, 2001, radiation portal monitors (RPMs) have been, and continue to be, installed at international border crossings (e.g., Fig. 1) as part of various programs to interdict radioactive materials of concern, such as nuclear weapons or special nuclear material (SNM). An overview of radiation detection at borders is provided in references [1–3]. The vast majority of these RPMs use plastic scintillator material for gamma-ray detection [4]. These detectors cannot provide detailed spectroscopic information; rather, they are gross-count detectors. With these gross-count detectors there are often radiation alarms observed arising from non-threatening sources of radiation, primarily from naturally occurring radioactive material (NORM) and persons treated with medical radiopharmaceuticals [5,6]. These alarms are real (not the false-positive alarms from statistical fluctuations or instrument faults) and are referred to as nuisance, or innocent, alarms.

Because all radiation alarms at a border crossing must be further investigated to determine if threat materials are actually present, the occurrence of nuisance alarms increases the cost and operational impact of radiation screening. Strategies to minimize nuisance alarms have, therefore, been under investigation. This article discusses a software algorithmic method for minimizing the number of NORM-induced nuisance alarms from RPMs in which plastic scintillation materials are used. This algorithmic method is referred to in this document by the term energy windowing (EW). Others have also referred to this method as spectral analysis and natural background reduction.

The use of the EW algorithm was first reported in a German patent application in 1997 by Trost and Iwatschenko [7] and later by Iwatschenko-Borho [8], Iwatschenko-Borho et al [9], and Rieck and Iwatschenko.
In these papers, the ability to discriminate NORM from man-made radiation sources in plastic scintillator gamma-ray detectors was reported. The method disclosed in the patent involved taking the ratio of the intensity from the low energy part of the scintillation light spectrum to the intensity in the higher energy part of the spectrum. This ratio turns out to be different for NORM and many man-made radiation sources of interest, particularly SNM, due to the difference in the incident gamma-ray spectrum and the resulting Compton continuum characteristic of plastic scintillator. Because this method required dividing the broad total-energy spectrum from a plastic scintillation material into a few smaller, non-overlapping "windows of energy," it became known as energy windowing.2

EW has also been shown to have a mitigating effect on a phenomenon known as shadow shielding. Shadow shielding is the decrease in the gamma-ray detector background level caused by the passing of a vehicle with dense cargo through a RPM. The vehicle and cargo temporarily shield the detector from the main sources of background radiation, which are generally the ground or pavement and any nearby brick or concrete structures. This reduction in background effectively negatively impacts the alarm sensitivity of the RPM. Over the past several years, extensive testing of the EW methods at Pacific Northwest National Laboratory (PNNL) has shown that it, in combination with gross-count thresholds, can reduce the rate of NORM alarms and mitigate the effects of shadow shielding [5]. Other non-cargo applications of RPMs (such as mail screening and personally owned vehicle monitoring) do not typically involve the observation of NORM, and, thus, do not tend to benefit from the use of EW.

The EW method has been implemented in commercial plastic scintillator-based RPMs built by several manufacturers including Ludlum Measurements, SAIC, and Thermo-Electron Corporation. These companies have tested the capability of EW associated with the screening of scrap metal, which was one of the major applications of RPMs before radiation screening at international borders became a significant endeavor. The use of EW for RPM screening of cargo traffic is a new application of the EW methodology, and, therefore, required verification to ensure continued sensitivity to SNM.

The purpose of this paper is to describe in detail various EW algorithms, and to show their success when used in RPM applications. This work is based upon data from hundreds of deployed RPM systems as well as laboratory testing. The material is presented in three sections. Section 2 gives a brief overview on radiation detection in plastic scintillator material and nuisance alarms. Section 3 delineates and compares gross-count and EW algorithmic methods. Section 4 applies EW to measurements taken under controlled experimental circumstances and to data from actual vehicle traffic for systems with two-window, three-window, and five-window implementations of EW.

2. Radiation detection for radiation portal monitors

2.1. Plastic scintillators

Radioactive materials emit various types of radiation, but only energetic gamma and neutron radiation can typically be used to detect these materials at distances appropriate to cargo screening. This paper will consider only the detection of gamma radiation. For this task, plastic scintillator material is used in the majority of RPMs as it is a cost-effective material that provides the large cross-sectional detector area needed for vehicle screening applications, and is physically robust for the challenging environmental conditions encountered at borders. Polyvinyl toluene (PVT) is the most common type of plastic scintillator material used for these applications. Hereafter, the term PVT will be used as a generic reference to plastic scintillators.

For passive screening applications the gamma-ray energy range of interest is from a few kilo-electron volts (keV) up to several million electron volts (MeV). Over this range of energy, Compton scattering overwhelmingly dominates the photo-absorption and pair-production interaction of radiation with matter.
interaction processes in plastic scintillator materials. Accordingly, there are no discernable full-energy peaks observed in PVT detectors, and isotopic identification is impossible. Moreover, the total energy deposited in PVT is not necessarily directly proportional to the original gamma-ray energy, but is spread over a broad energy range (Compton continuum). This is opposed to detector materials for which photo-absorption is significant, such as thallium-doped sodium iodide [NaI(Tl)] crystals, where all of the energy of the incident gamma ray is often deposited as an easily discernable full-energy peak [11,12]. It is this full-energy peak that is directly proportional to the incident energy and, along with the information in the full spectrum, can be used for spectroscopy.

The response in a PVT detector is, nonetheless, somewhat dependent on the original gamma-ray energy, as a spectrum obtained from incident high-energy gamma rays will have a different Compton edge than a spectrum obtained from incident low-energy gamma rays. Therefore, crude spectroscopic information is available even in PVT. This crude information can be exploited to differentiate gamma rays from low- and high-energy sources, if the signal is binned using a multi-channel analyzer (MCA).

The location of any Compton edge in the recorded PVT spectra (even under the best circumstances of a dominant, isolated high-energy gamma ray) has some uncertainty because the poor intrinsic resolution in PVT causes this “edge” to smear out into a broad distribution. In addition, the collection of light varies across a large piece of PVT plastic, and the efficiency of the photomultiplier in converting scintillation light into recordable electronic signals can change with temperature, thus shifting the Compton edge, and further increasing the uncertainty in its location. Therefore, only a limited number of energy bins, or windows (also called regions-of-interest), are practical for extracting the available information from PVT plastic. The optimum number of windows depends primarily on the number of targeted materials, one window for each separable Compton edge. Other factors such as the size and quality of the plastic, and counting statistics of the measurement may limit the number of useful windows.

As shown in this paper, an EW algorithm based on a set of two or more energy windows used in conjunction with a gross-count algorithm can avoid alarming on most NORM material without missing targeted sources.

Radiation portal monitor systems accumulate an average background radiation count rate when no vehicles are present. Data obtained when vehicles are in the portal are compared to this background rate with various algorithms in order to determine an alarm state. Data are typically sampled at a rate of 10 samples per second and averaged to produce 1-s time bins on which alarm analyses are performed. More sophisticated time apodization methods with Gaussian filters are also possible rather than just simple averaging. While it is possible to vary the time over which the data are averaged, one second is a reasonable compromise for obtaining sufficient statistical data for sensitivity to sources moving at speeds of a few miles per hour. The optimal averaging time of about one to a few seconds is determined by the speed of the vehicle being screened and the physical distribution of the source. Some speed dependent algorithms are used that adjust the averaging time to optimize the sensitivity to point sources as a function of speed.

2.2. Thresholds and nuisance alarms

The primary source of radiation detected in an RPM is normal environmental background radiation. The level of this background radiation is dependent on the locale, but it usually maintains a fairly stable average value that depends to some extent on the weather. Rain and atmospheric pressure changes can cause background from radon daughter levels to change rapidly. The distribution from a typical background counting rate with an arbitrary normalization is shown by the dot-dashed “Background” curve in Fig. 2. This shows schematically the typical distribution of data from all panels of a RPM, irrespective of the type of traffic lane. For this figure, background values associated with about 3500 vehicles in the narrow lanes of a site, and 1900 vehicles in the wide lanes, were included.

Note from these curves that the statistical behavior of radioactive decay and the environmental variations give rise to a skewed Gaussian-like shape. Also note that the high-count-rate tail on the background distribution arises from changes in the background environment surrounding the detector, including weather and possible nuisance sources in proximity to the detector. To avoid false-positive alarms from statistical fluctuations in the background radiation, the gross-count alarm threshold of the RPM is usually set significantly above the average level (peak of the distribution curve) of the background radiation.

Another source of radiation detected with RPMs is not necessarily of concern and arises from persons or cargo within vehicles. Examples of this type of non-threatening radiation sources are shipments containing normal commercial items, such as tile or cement, or people who, for medical reasons, have been treated with radiopharmaceuticals. All of these sources in vehicles are detected as an increased level of radiation above the average background level and, depending on the alarm threshold, may cause an alarm. These types of radiation are classified as “nuisance”

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3It may be possible for more energy information to be extracted if the energy was binned with many channels (256 or greater); however gain stabilization mechanisms would need to be employed as well.

4Apodization is the method of folding time sequence data with a shape function to bring a distribution smoothly to zero. This operation can enhance the performance of an algorithm to certain source scenarios such as a point source versus a distributed source.

5Other panels from other sites for other sets of vehicles show this same pattern.
radiation, giving rise to nuisance alarms, since they represent real increases in radiation above background.

The dashed “Vehicles” curve in Fig. 2 shows a general representation of the normalized distributions of the average gross-count rate when vehicles are present. As mentioned above, vehicle average count data were examined for the four panels of RPMs in narrow and wide lanes for the same sets of vehicles that generated the background data plotted in the dot-dashed “Background” curve of Fig. 2. All RPMs showed this same pattern irrespective of the site, vehicle, and RPM manufacturer. The radiation distribution of this averaged data from a wide range of cargo vehicles shows a shift toward low-count-rate from the shadow shielding effect. This skewed Gaussian-like distribution also displays a high-count-rate tail resulting from NORM and other sources in vehicles. For comparison, an isolated point source of sufficient strength would produce a Gaussian peak, arbitrarily placed at about 4800 counts per second (cps), as shown schematically by the solid curve in Fig. 2. The width of a Gaussian distribution is described in terms of the fluctuation of the distribution from the mean value. This fluctuation is often quoted in units of standard deviation ($\sigma$). Since the generally observed Gaussian distribution is the large count rate limit of a Poisson distribution, $\sigma$ is equivalent to the square root of the number of counts, $N$, accumulated in any given counting interval:

$$\sigma = \sqrt{N}. \quad (1)$$

For the point-source example assumed in Fig. 2, the radiation has an average radiation level well above the background curve centroid. The differentiation of this test source from the background distribution is relatively easy with the proper selection of a gross-count threshold setting.

As an example, for 99.9% detection efficiency, the threshold should be set at about $3\sigma$ below the mean of the detected distribution of the test source value. For a 1-s measurement period and the count rates shown in the figure, the test source would produce about 4800 counts, resulting in a 99.9% detection probability at a threshold of about 4592 counts. Statistically, the test source would nearly always produce an alarm (~0.1% false-negative alarms) at this threshold. However, the high-count-rate tail of the radiation from cargo vehicles shown in this simple example would certainly cause nuisance alarms as it cannot be discriminated from the test source with a simple choice of a gross-count threshold. Because commercial cargo contains NORM and medical isotopes, simple gross-count thresholds can generate many nuisance alarms. Depending on the operation of vehicle screening and the nuisance alarm rate, the gross-count thresholds might have to be adjusted to a higher (less sensitive) value to reduce the operational impact of handling too many nuisance alarms.

### 2.3. Description of NORM and SNM signatures

The utility of the EW technique is based on the fact that most of the gamma-ray emission from SNM sources comes at a significantly lower energy than most of the emission from NORM. To illustrate this point, two NORM sources (tile and fertilizer) and two man-made sources, plutonium and highly enriched uranium (HEU), are compared to background. Both bulk NORM sources were contained in wooden boxes approximately $0.9 \text{ m} \times 1.2 \text{ m} (3 \text{ ft} \times 4 \text{ ft}) \times 1.2 \text{ m} (4 \text{ ft})$ high. The radioactivity from tile is primarily from $^{40}\text{K}$ (half-life $1.28 \times 10^5 \text{ y}$) decay and radionuclides in the uranium and thorium decay chains. The radiation from the fertilizer is primarily from $^{40}\text{K}$. A number of measurements have also been performed with other NORM materials, in which the uranium and thorium decay chains dominate the radiation signature, with similar results to those described here. The weapons-grade plutonium (WGPu) source (principally $^{239}\text{Pu}$, half-life $2.41 \times 10^4 \text{ y}$) was $99.4 \text{ g}$ of PuO$_2$. The Pu was doubly contained in sealed schedule-80 stainless steel pipes that provided approximately 10 mm of shielding. Because of the stainless steel shielding, radiation from the $^{241}\text{Am}$ that was present in the sample from the decay of small concentrations of $^{241}\text{Pu}$ is highly attenuated. The 93.1% enriched HEU ($^{235}\text{U}$; half-life $7.04 \times 10^8 \text{ y}$) source had a total mass of 123 g and consisted of a number of stacked foils in a thin container.

Radiation from these four sources was measured at 2 m perpendicular to the center position of the front surface...
area of a single RPM panel. No additional shielding was placed between the sources and the detector for the measurements shown. Background measurements were taken before and after the source measurements. The NORM measurements were taken for 60 s, but due to a limitation of the MCA, the WGPu and HEU sources were measured only for 5 and 20 s, respectively. The WGPu and HEU data were then normalized to 60 s for comparison with NORM. These spectra were taken and renormalized only to illustrate the detector response to these sources. For comparison, a typical vehicle scan with a deployed RPM takes less than 20 s.

As seen in Fig. 3A, NORM and background radiation have very similar shapes over most of the PVT energy spectrum. The intensities of the spectra differ depending on the source (tile, road salt, fertilizer, etc), cargo (size, shape, etc), and isotope distribution (K, uranium decay series, etc). However, these gross signal variations do not play an important role once a normalizing ratio is taken.

The gross signal distributions of the WGPu and HEU sources (plus background) are also shown in Fig. 3B. Although the source spectra are gross, as opposed to net spectra, the corresponding source only will be used when referring to the spectra. Here, the distinct differences between these sources and background are plainly visible in the lower channels (low energy). Because there is a lack of significant high-energy gamma rays from these sources, the distribution of counts in the channels with higher numbers is very similar to background. This difference in the energy distribution is the underlying feature that allows the EW discrimination of man-made sources, such as these, from NORM sources.

3. Algorithms for radiation detection

The goal for EW algorithms in RPM applications is to use the crude spectroscopic information available from PVT to discriminate NORM from other radiation sources. A multi-channel analyzer with 256–512 channels is typically used to accumulate counts at various "energies" from these detectors. In the simplest approach, these channels can be segregated into energy regions or windows. These data can be binned into several different energy regions in order to obtain a rough measure of the original energy of the gamma rays entering the PVT material. The number of windows can be from one up to the maximum equal to the number of channels in the analyzer, but as would be expected, there are a number of windows above which there are diminishing returns. Taking ratios between the counts in the various energy windows should provide discrimination between sources, such as NORM, and man-made radioactive sources like SNM. There are three pragmatic choices needed for implementing an EW algorithm: what regions of energies define the windows, how many of these windows are needed, and what ratio, or combination of ratios of the counts in the selected windows enables SNM to be differentiated from NORM.

3.1. Gross-count algorithms

The first approach to using energy information in RPM applications might be to compare the gross-count rates with a vehicle present to the background rates in each of the various possible energy windows using a gross-count threshold algorithm. A typical gross-counting threshold implemented in commercial RPM equipment is based on the background counts in a set time interval and the associated variations or fluctuations. A typical gross-count threshold is calculated as

\[ T = N + K\sqrt{N} \]  

Fig. 3. Spectra from PVT for (A) NORM radiation (fertilizer and tile) and background, and (B) HEU, WGPu, and background to illustrate the differences in the spectra at low energies (low channel number). Note the different scales used in the upper and lower graphs. Due to the collection time differences, the WGPu and HEU spectra have more fluctuation at high energies.
where \( T \) is the threshold counts in a 1-s time interval based on the averaged background, \( N \) (counts in one second), and the standard deviation of that background, \( \sqrt{N} \), for Gaussian statistics. The constant \( K \) is a multiplier ("sigma multiplier") that determines the threshold value above background in units of background standard deviations.9

The reason that this particular choice for a windowed gross-count threshold algorithm fails when applied to actual data is seen from the spectra shown in Figs. 3A and B. As seen in Fig. 3A, the counts from NORM sources are elevated across the entire spectrum including the low energies where SNM (Fig. 3B) would enhance the spectrum. Hence, NORM discrimination cannot be accomplished with a simple gross-count approach.

### 3.2. Energy windowing algorithms

To discriminate NORM from other sources, a more sophisticated approach than simple gross counting in each of the several possible energy windows must be used. The idea is to compare the shape of the energy distribution to the background shape and to quantify the similarity or difference. From Fig. 3 it is evident that, although the NORM sources have radiation signatures with greater intensity than background, the shape of the energy distributions is very similar. This is because NORM and background materials contain the same radioactive isotopes, namely \(^{40}\text{K}\) and isotopes in the uranium and thorium decay chains. In contrast, man-made isotopes, such as SNM, have spectra with more low-energy radiation. It is clear from these plots that the shapes of the energy distributions for these sources are not the same. Radiopharmaceuticals, the other significant nuisance source, are not discussed here since, like SNM, they also produce a low-energy signature and EW is thus not useful for discrimination of such sources from SNM, but they can be discriminated from NORM [13].

Consider a source that emits a mono-energetic gamma-ray and an EW scheme in which two windows are employed, one for the lower half of the spectrum extending from the detection threshold up to and slightly above the Compton edge of interest, and the other covering the remaining portion of the high-energy spectrum. Placement of the window boundary above the Compton edge of the gamma ray of interest optimizes the statistical precision of the alarm algorithm. Once the counts in each channel have been sorted into these two windows and summed, the numbers must be compared to the values for background in the same windows. The difference or similarity of the counts in the energy windows to the background counts in the same windows can be quantified by various methods.

One simple method is to normalize the counts in each energy window (a range of channels) to the counts in the high-energy window and compare that normalized ratio to the corresponding background ratio:

\[
R_{\text{EW}} = \frac{N_{\text{EW}}}{N_{\text{H}}} \quad (3)
\]

where \( N_{\text{EW}} \) is the number of counts in the specific energy window and \( N_{\text{H}} \) is the number in the high energy window, both when a vehicle is present. The comparison to the background might take the form of a difference, which could be a net ratio or could be a ratio of the measurement to the background (a ratio of ratios). Or the comparison might take a form similar to the gross-count algorithm (Eq. (2)):

\[
R_{\text{EW}} > R_B + K\sigma_{R_B} \quad (4)
\]

where \( R_{\text{EW}} \) and \( R_B \) are the ratios for the source being measured and background windows, respectively, \( K \) is a multiplier that accounts for the difference in sensitivity and geometry of monitors in different lanes of traffic, and \( \sigma_{R_B} \) is the statistical standard deviation for the background ratio. Using standard statistical variance propagation of functions of random variables, \( \sigma_{R_B} \) can be derived as given in Eq. (5):

\[
\sigma_{R_B} = R_B \sqrt{\frac{1}{N_{\text{LB}}} + \frac{1}{N_{\text{HB}}} - 2\rho \frac{\sqrt{N_{\text{LB}}N_{\text{HB}}}}{N_{\text{LB}}N_{\text{HB}}}} \quad (5)
\]

where \( N_{\text{LB}} \) and \( N_{\text{HB}} \) are the number of low and high energy window background counts, respectively, and \( \rho \) is the correlation coefficient for \( N_{\text{LB}} \) and \( N_{\text{HB}} \). This concept can be extended to handle multiple energy windows.

Although an exhaustive investigation of the various possibilities for analyzing the data has not been performed, it has been demonstrated that the actual form of the energy window ratio is not critical. Two other ratios have been investigated and found to give equivalent results. The first is

\[
R_{\text{EW}} = \frac{N_{\text{EW}}}{\sum_{i=1}^{n} N_i} \quad (6)
\]

where \( N_i \) is the number of counts in the \( i \)th window of a multi-window system. This is very similar to the initial ratio discussed above except the denominator is now the total count over all windows instead of just the counts in the highest window. Another method is given by Trost and Iwaschenko [7]:

\[
R_C = N_L - \frac{N_{\text{LB}}}{N_{\text{HB}}} N_H \quad (7)
\]

where \( N_L \) is the number in the low energy window, and \( R_C \) is the compensated ratio that is approximately equal to zero when the measured counts in the low-energy region are equivalent to the background-compensated counts in the high-energy region (i.e., the shape is the same as the background). In this formulation, the counts are always divided into two regions, a low and high region, even in a

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9Because the value of \( N \) is determined without a vehicle present, this expression shows how any depression of the vehicle-present background, e.g. \( N' < N \), leads to a decrease in alarm sensitivity set by the value \( T \), when it should be a smaller value. A lower threshold can compensate for this, but with a resulting higher nuisance alarm rate.
multi-window implementation, by summing groups of windows.

There are several possible variations of the EW algorithms that are based on ratios of regions of interest, the most common being those in Eqs. (3), (6), and (7) above. Operationally, since systematic effects tend to dominate over statistics, our studies indicate that there is little or no advantage of one variation over another. Studies by the authors have been made of optimizing the number of energy windows and the locations of the window edges. These studies generally show that the window edge should be placed at the Compton edge of the source of interest. Theoretically, it is possible to divide the energy spectrum into a large number of energy windows. However, too many windows dilute the ability to discriminate target sources. While the optimal number of windows depends on the targeted sources, three to five windows are found to be practical. The discussion of a two-window EW implementation will be continued to simplify the explanations and mathematics. However, the extension to EW with more than two windows is straightforward. After the discussion of the two-window system, multi-window systems will be covered. An analytical alternative to the EW approach is to apply full spectral analysis methods, such as template matching, to PVT-based RPM systems. Such approaches are now under investigation and the results will be reported in a separate paper.

3.3. Statistical viewpoint

From a statistical standpoint, EW may at first appear to be a poor approach if the counts are obtained without an MCA. In that case, the signals above each window boundary (determined by the setting of a signal discriminator) are counted, and the counts in individual windows obtained by subtraction. The statistical error in each energy bin appears to increase for the windowing technique when compared to the total gross-count mode if the statistical error is simply added in quadrature, that is, for example, if \( \text{Variance}(\text{window1}) = \text{Variance}(\text{total} - \text{window2}) \) were incorrectly taken in quadrature to be \( \text{Variance}(\text{total}) + \text{Variance}(\text{window2}) \). However, correlations need to be taken into account because the count rates obtained by this subtraction method are maximally correlated (since they are exactly the same data obtained from different window thresholds). This would give the correct expression as \( \text{Variance}(\text{window1}) = \text{Variance}(\text{total}) + \text{Variance}(\text{window2}) - 2 \times \text{Covariance(} \text{total}, \text{window2}) \), the standard statistical result for the variance of the difference of two random variables [14]. The statistical error for the energy window, accounting for correlations, can thereby be shown to be less than the statistical error for the total count rate in this case. If the detector system has an MCA, the statistical error on any one window is again less than the statistical error for the total count rate.

As an example of the sensitivity of the various algorithms, consider a simple two-window system with a background count rate of 2000 cps in the low window and 1000 cps in the high window. For a 1-s measurement, the total is then 3000 counts with a standard deviation of about \( 55 (\sqrt{3000}) \). The standard deviations on the low and high-energy window counts are approximately 45 and 32, respectively. These are both less than the standard deviation for the total counts (55). Therefore, if a targeted material has counts only in the low-energy window, dividing the counts into energy windows increases the sensitivity (signal-to-background or signal-to-noise) compared to total counts even when the same gross-count threshold algorithm is used for each window. For a detection threshold level set at three standard deviations, approximately 135 counts (3 \cdot 45) above background in the low-energy window would be detectable with the gross-count algorithm. Extending this simple example to a ratio algorithm and using the approach given in Eq. (2), the statistical standard deviation of the ratio is approximately \( 0.02 \) (from Eq. (5), assuming maximal correlation with \( \rho = 1 \)). The same 3 standard deviations for the EW ratio from Eqs. (2) and (5) results in a detection of approximately 60 counts\(^{10} \) in the low-energy window, which is about twice as sensitive as the gross-count algorithm. Thus, EW ratios do not suffer on purely statistical fluctuation grounds.

However, the discrimination power of any method depends both on statistical and systematic fluctuations. The above simple argument, has only considered statistical fluctuations and ignored any systematic variations. As will be illustrated in following sections, the systematic variations such as shadow shielding dominate the total fluctuations and must be taken into consideration as well.

In the above paragraphs, discrimination was discussed both in terms of gross-count algorithms for individual energy windows and EW ratio algorithms. The EW ratio algorithm appears to have NORM discrimination capability while the gross-count algorithm does not. In the following sections, the results of EW studies with experimental measurements with SNM samples and data from operational RPMs are presented. The EW approach can be implemented with a varying number of windows. In the next few sections, examples will be provided of two-window, three-window, and five-window EW implementations to show the variety of possible implementations, and their limitations. As will be shown, the five-window EW implementation provides the greatest ability to discriminate NORM and threat sources.

3.4. Discrimination with energy windows

As discussed above, the optimal window discriminator setting is generally just above the Compton edge with a

\(^{10}\)The ratio of the low-energy to high-energy window counts (2000 and 1000, respectively) is 2. A 3-sigma shift would thus be a value of 2.06 for the ratio. Again with the low-energy and high-energy window values given, it takes 60 counts in the low-energy window to give this ratio.
window for each targeted material. Consider the spectra shown in Figs. 3A and B and a selection of three energy windows encompassing channels 1–20 (low energy), 21–60 (medium energy), and 61–256 (high energy). The entire HEU source strength is captured in the low-energy window, while the WGPu source strength appears in both the low- and medium-energy windows.

The gross-count rates for each of the NORM, SNM, and background sources are summed in the low-, medium-, and high-energy windows, with the results displayed in Fig. 4. From those results, it can be seen that the HEU counts are greater in the low-energy bin only, while the WGPu counts are above background in both the low and medium energy bins. Assuming a gross-count threshold applied separately to each energy window, it is evident that NORM discrimination with gross-counts is difficult as NORM also has counts above background in the lower energy windows. A more sophisticated approach is required than using just gross-counts.

Applying Eq. (3) to the data shown in Figs. 3A and B yields the ratio results shown in Figs. 5A and B illustrating ratios in each window for the background, NORM, WGPu, and HEU. For this example of three windows, only low-energy and medium-energy ratios to the high-energy window are formed, since the ratio for the high-energy window to itself has a value of one by definition of the normalization process (Eq. (3)). The NORM ratios as shown in Figs. 5A and B are seen to be very similar to the background ratios. The ratios are similar even though the total counts for the sources are very different (shown in Fig. 4). There are, however, large differences in the WGPu and HEU ratios compared to the background. The medium-energy ratio for HEU corresponds to background as expected from the spectral plot in Fig. 3. Although the specific SNM sources used for these measurements are not representative of all cases, this study illustrates the capability of these ratios to discriminate NORM from lightly shielded SNM. The applicability to vehicle screening data is discussed in the following section.

4. Application to vehicle traffic

This study was extended to actual vehicle traffic data in commercial lanes with commercial cargo RPMs. The RPM systems used have a data acquisition subsystem that allows partial spectroscopic information to be obtained for subsequent data analysis. For these systems, gamma-ray events detected in the PVT radiation sensor panels are converted into signals proportional to the gamma-ray energy deposited, and these are stored in energy bins. One of these commercial systems uses a two-window implementation of EW, and the other uses a five-window implementation of EW. To simplify the mathematics and explanation, we first discuss the two-window EW algorithm applied to real traffic data available from this
commercial system. While the principles discussed are the same, systems with three or more windows show a greater discrimination capability than a two-window system; the five-window system is discussed later. For this two-window analysis, Eq. (6) is used and the difference ratio, $R_{\text{dif}}$, is computed with the equation:

$$R_{\text{dif}} = \frac{N_L}{N_L + N_H} - \frac{N_{LB}}{N_{LB} + N_{HB}}$$

where $N_L$ and $N_H$ are the counts in the high- and low-energy windows and $N_{LB}$ and $N_{HB}$ are the counts in the high- and low-energy background windows, respectively. The background counts are obtained between vehicles. Alarming criteria are typically set on the total gross-count rate and can additionally be set to alarm based on this ratio between windows (EW alarms).

Since the count rates from the deployed RPM systems are affected by weather changes, it is worth commenting on the environmental effects on these systems. Data trend studies carried out for more than a year with multiple systems deployed on both the northern and southern borders show that the EW ratios and gross-count values above background are stable. The impact of changing temperatures and other weather conditions on RPM systems and EW will be the subject of a future publication.

4.1. Application of EW ratios—two-window system

Continuing with the two-window example, Figs. 6A and B show a typical vehicle “profile” scan. The data were collected every 0.1 s as the vehicle passed through the portal. This profile was gross-counts of the sum of the counts from the four panels in a cargo RPM. This particular case was for a tractor-trailer truck transporting clay material, a NORM source. Fig. 6A displays the raw count rate in the high- and low-energy bins, i.e. channels 1–100 (low energy) and 101–250 (high energy). The low-energy counts show a dramatic increase as the trailer passes through the portal, with a similar fractional increase in the high-energy bin. However, the ratio of the two counts, as shown in Fig. 6B, indicates that this commodity resembled the shape of background, that is, the ratio showed no difference from the background ratio, indicating that it was NORM. This is one example of many vehicles analyzed in this study where NORM would have generated a gross-count alarm, but little change in the ratio profile was observed.

4.2. Vehicle shadow shielding

One major effect of a vehicle passing through a RPM is the shadow shielding (Fig. 2 and Fig. 7A) that the vehicle provides to the normal background radiation that is incident on the detectors [15]. This effect complicates the detection of radioactivity because the signal is suppressed to a lower value below the background level as the vehicle enters the RPM. However, the background that is used to calculate the gross-count threshold for comparison to the measured data is collected before the vehicle enters the RPM and is, therefore, not suppressed. This effect lowers the sensitivity of the gross-count measurement since the radiation in the vehicle must be greater than the suppression plus the threshold values in order to generate an alarm [See footnote to Eq. (2)].

The exact amount that the baseline is depressed depends on the vehicle (size, shape, construction, etc.) and the material being transported. The suppression factor, therefore, cannot be known before the measurement. Various schemes to follow and correct for this shadow shielding effect have been investigated, but there is not a simple, reliable solution. The problem of correcting for shadow shielding is further complicated because for most cargo-carrying vehicles, there is a gap between the tractor and the trailer. This gap shows up as a spike in radiation as that gap passes the detector. There is no easy method to discriminate between
an increase in count rate as the gap between tractor and trailer passes the RPM or a real radiation source in the vehicle.

An EW algorithm can help mitigate this shadow shielding effect [1]. Since the shape of the energy distribution is compared to the shape of the background in the EW approach and not the absolute value of the radiation response, the EW approach should, in principle, be much less sensitive to background suppression. The shadow shielding from the vehicle is assumed not to change the relative ratio of the counts in the EW bins, which is generally true. There are indications that the background is suppressed in the EW bins differently, as the energy dependence of gamma-ray attenuation would suggest, but this is a minor effect that will be discussed in the following section. Fig. 7A shows a typical profile taken from the vehicle study for the high-energy and low-energy bins as a commercial vehicle containing no NORM passes through a RPM. These profiles are the sum of the total counts from all four panels in the cargo RPM system. There is no indication of radiation in this profile and the background is suppressed in the RPM as the vehicle passes through the RPM. Both the low- and high-energy regions have suppression of the background rate although it is difficult to quantify for the high-energy counts (lower profile in Fig. 7A). Fig. 7B shows the ratio of the low-energy to total counts for the same vehicle profile. The ratio is unaffected by the suppression of the counts and is statistically constant across the profile. This ratio profile is a typical example of many such analyzed in the course of this study, all of which appear very stable with regard to shadow shielding. These profiles are indicative that shadow shielding can be mitigated to a large extent with the summed profiles and the EW algorithm.

4.3. Multiple vehicle analysis

The above discussion focused on an example of a single vehicle profile to illustrate the advantages of the EW technique. It is also useful to perform a multi-vehicle analysis and investigate average behaviors. Data from a deployed radiation portal monitor with four panels for over 700 vehicles are shown in Fig. 8, where for clarity, only data from two panels, one upper and one lower, plus the sum of all four panels, are shown. In the figure, the temporal signals from the passage of the 700 vehicles are overlaid, with the vertical axis being net signal (background subtracted) and the horizontal axis being time. Because vehicles move at slightly different speeds through the RPM, some vehicles are longer than others, and some tractors have no trailers; the data were normalized to a 20 s time profile to allow comparison. This small time normalization has little effect on the statistics, since the count rates are large.

The two graphs on the top-left and middle-left of this figure are net-counts for one top and one bottom RPM panel, respectively. The graph on the lower-left of Fig. 8 is the sum of the count rates from all four panels. The graphs on the upper-right and middle-right are differences between vehicle EW ratios and background EW ratios for the same panels shown to the left. The dashed line shown in the left graphs indicates the background level determined when no vehicles are present; the solid curve is the statistical average of all the data from 700 vehicles. At a point of maximum suppression along the time profile, an approximation of a standard deviation over the vehicle profiles can be obtained from the vertical distribution of the dark band of profiles. Pick, for example, the values at 6 on the x-axis in the upper left graph of Fig. 8. The average (solid curve) is clearly below zero, and the range in the bulk of the data is about 400 counts. Using a common statistical approximation method, by dividing this range by 4 (giving 100), then in turn dividing this result by the square root of 700, the standard deviation of the estimated mean
(standard error) can be approximated. This means that the estimated standard deviation is about 4 counts. Thus, statistically, and observationally, the average (solid curve) is very significantly different than zero for the distribution of the individual panels for the 700 vehicles as a result of shadow shielding.

Fig. 8. Total counts for each of 700 vehicles passing through a 4-panel RPM. The two graphs on the top-left and middle-left are net-counts for one top and one bottom RPM panel, respectively. The solid lines in these plots show the average of the data, and indicate a shadow-shielding effect. The graphs on the upper-right and middle-right are differences between vehicle ratios and background ratios for the same panels shown to the left. Top RPM panels and RPM bottom panels show differences in the average values (solid lines) that, while small, are statistically different from background (dashed line). The plot on the lower-left is the count data for sum of all panels. The plot on the lower-right is the ratio for the sum of all four panels, showing the averaging out of the shadow-shielding effect in the summed ratio.
To form the energy ratio in this study, Eq. (8) was applied to the data. The results are shown in the pair of graphs in the upper-right and middle-right in Fig. 8. Analogous to the estimation method above of standard deviation, the average ratio shown (solid curve) in these graphs is also very statistically different from zero. The fact that the lower RPM panels and upper RPM panels show depression and enhancement, respectively, of the ratio is indicative that shadow shielding does have some effect (due to differences as a function of energy in attenuation in the cargo) even on the ratio when compared to the deviation of the average counts from zero (background), although this effect is less than for the gross-counts.

However, as the upper and lower panels are affected in the opposite direction for the ratios, a simple sum over all panels eliminates the shadow-shielding effect on the average ratio. Applying Eq. (8) to the sum of all panels yields the results for the ratios shown in the lower-right of Fig. 8. As seen in the figure, the positive and negative deviations of the average ratio from the upper and lower panels, respectively, for 700 vehicles cancel when summed together. Thus, the EW algorithm applied to the sum of the panels shows no shadow-shielding effect, and therefore largely eliminates this important effect from impacting the EW alarm method. This is another significant advantage of the EW method over the gross-count alarm method.

4.4. Injection studies—five-window example

In the following discussion, a commercial five-window EW system is used as the basis of the discussion on the advantages of a multi-window EW implementation to detect SNM.

4.4.1. Five energy window implementation

As discussed above, there are differences in the plastic scintillator energy spectra of NORM, background, and SNM. Consider taking the channel-by-channel ratio of the counts in a net source spectrum to the counts from a background spectrum. The figure illustrates to show the capability of EW. A ratio of one means there are the same number of counts in the net source spectrum as in the background spectrum. The figure shows that the $^{57}$Co and HEU sources differ from background within window 1, that the $^{133}$Ba and WGPu sources differ from background within windows 1 and 2, and that the DU source differs from background within windows 2–4. None of these sources show a significant deviation from background in window 5.

In the injection studies discussed below, each of these ratios is normalized to a sum of higher windows, in a variation on the method used in the two-window and three-window approach discussed earlier. This means that the ratios of the total counts in each of these energy windows to the counts in the remaining windows is formed (e.g., the ratio of counts in window 1 to the number of counts in windows 2–5 is formed). This can be expressed by a generalization of Eq. (8):

$$R_j = \frac{N_j}{\sum_{i=j+1}^{n} N_i} - \frac{N_{Bi}}{\sum_{i=j+1}^{n} N_{Bi}}$$

where $N_j$ is the number of counts in a group of windows with the highest window being the $j$th window of a multi-window system, $N_{Bi}$ is the number of counts in a group of windows with the highest window being the $j$th window of the background spectrum, $N_i$ and $N_{Bi}$ are the number of counts in higher energy windows than the $j$th window. The ratio for the first window is referred to as “Ratio 1,” and so forth. For the five-window system used here, the four energy window ratios are: Ratio 1 is the ratio of the counts in window 1 to the combined counts in windows 2–5; Ratio 2 is the counts in windows 1 plus 2 to those in windows 3–5; Ratio 3 is the combined counts in windows 2 and 3 to those in windows 4–5; Ratio 4 is the combined counts from windows 2–4 to those in window 5.
4.4.2. Application to vehicle data

Above, the use of EW to eliminate the impact of shadow shielding and to discriminate NORM was discussed. However, the use of two- and three-window systems to distinguish all potential sources of interest relative to NORM and background can be limited. As might be expected, while laboratory experimental data exist for SNM, such data are not available from vehicles at ports of entry. However, injection studies with actual vehicle data from ports of entry can be performed to simulate the presence of SNM in commerce. These studies are discussed below and illustrate the capability of EW for SNM discrimination.

It is worth emphasizing that when the EW method is used, the gross-count threshold is still utilized, perhaps at an elevated level, resulting in a reduced numbers of NORM alarms from the gross-count threshold, while the EW threshold adds very few new NORM-related alarms. It should be realized that the EW approach cannot improve the inherent sensitivity of the RPM, but can simply provide targeted operational sensitivity without adding nuisance alarms by utilizing the available sensitivity. The gross-count threshold approach could reach the same operational sensitivity as EW, but with a severe nuisance alarm rate.

Operational testing of the EW concept in the field with sources packed into normal cargo loads in a randomly selected tractor-trailer configuration is not feasible. Alternatively, it is possible to use a large volume of collected data from deployed RPMs and randomly inject a simulated source into the data during subsequent data processing. The raw RPM data are in the form of energy spectra (as counts in each window) taken at 0.1-s time intervals during the passage of a vehicle (e.g., see Fig. 6). The injected counts are added to each time slice for the study at the appropriate amplitude for the source location. This is called an injection study, in which it is assumed that randomly selected profiles from archived vehicle data now contain some amount of targeted material. The simulation is repeated multiple times while varying the number of injected counts from the source. The resulting injected spectra are analyzed with the gross-count and EW algorithms to determine the system response. The results are displayed as detection probability versus the number of injected counts, as seen in Figs. 10–12.

For the study, thresholds must be assumed for both the gross-count and EW thresholds. The thresholds for this study were chosen to have a nuisance alarm rates less than 1.5% and 0.5% for gross-count and EW, respectively. To control EW alarm levels, a threshold consistent with a value of 4–5 standard deviations above zero was used in this study.

One injection study used the records from a random selection of approximately 20,000 vehicles with the source injected at random locations along the vehicle record. The injected source was varied over several cases, including $^{57}$Co, $^{133}$Ba, and DU, and the window ratios were...
calculated. For $^{57}$Co, Fig. 10 shows that Ratio 1 is the most sensitive, i.e. there is 95% detection at the lowest number of injected counts; Ratio 2 is slightly less effective; Ratios 3 and 4 are insensitive even relative to the assumed gross-count threshold. This is to be expected, since about 70% of the total counts for $^{57}$Co are in the first window (see Fig. 9).

For $^{133}$Ba, Fig. 11 shows that Ratio 2 is the most sensitive. Ratio 3 is intermediate in effectiveness, while Ratios 1 and 4 and the gross-count threshold are much less effective. This is to be expected, since most of the total counts for $^{133}$Ba are in the first and second windows (see Fig. 9).

For DU, Fig. 12 shows that Ratio 3 is the most sensitive followed by Ratio 4, but Ratios 1 and 2 are totally ineffective. As in the other cases, the gross-count approach is less sensitive than the optimal ratio to the presence of the targeted material.

To increase confidence in the accuracy of the injection studies, laboratory measurements were performed with sources. Fig. 13 shows the result from one such measurement with 2 kg of DU walked through an RPM, displayed as ratio value versus sample number (time in 0.1 s intervals). The figure shows the ratio increase and decline as the source passes through the RPM. It is clear in this example that Ratios 3 and 4 are sensitive to the presence of DU in the RPM, but Ratios 1 and 2 are insensitive to DU. This is consistent with the window placement as displayed in Fig. 9.

Another injection study performed by the authors with approximately 20,000 vehicles illustrates the NORM discrimination power of the EW ratio. In this study, the NORM alarm rate using a gross-count threshold was 2.65% (530 vehicles) whereas the EW ratio statistic resulted in only 0.37% NORM alarms (74 vehicles) for a greater operational sensitivity to targeted sources. The study showed that for a fixed alarm rate of 0.37%, much greater sensitivity to targeted sources was obtained when the EW ratio statistic is used versus the gross-count threshold. While these percentages of vehicles potentially sent to secondary inspection do not seem large, for a very busy border crossing, 20,000 vehicles might represent a few days of operation.

This work, as well as other experiments and injection studies not presented here, show the effectiveness of a multi-window EW implementation.

5. Conclusions

The purpose of this paper has been to describe energy windowing algorithms and to show how they work in RPM applications. Simply stated, the EW method is carried out by partitioning the full-energy spectrum from PVT detectors into a few windows, and then to form ratios between the count rates in the various windows. These ratios provide a basis for discriminating between sources, such as NORM, and man-made radioactive sources like SNM. When applied to RPM cargo screening, such NORM discrimination capability can result in reduced nuisance alarms that can otherwise hinder the flow of traffic and commerce. A reduction in the number of nuisance alarms also allows ports-of-entry to use more sensitive thresholds to certain targets, maintaining a high level of vigilance, while not interfering with commerce.

The studies presented in this paper indicate that EW can indeed discriminate against NORM and maintain sensitivity to materials of interest, specifically SNM in certain scenarios. These studies included application of EW experimental measurements for known SNM sources as well as application to data from actual vehicle traffic. In particular, it was shown that a simple three window EW scheme allows NORM discrimination with excellent sensitivity to modest amounts of SNM. It was also shown that the shadow shielding of an RPM by commercial vehicles results in background suppression that reduces the alarm sensitivity of gross-count algorithms. The EW ratio, used with a sum of panels, reduces this loss of sensitivity due to shadow shielding.

With these positive results, a set of ratio and gross-count criteria have been developed that can be used together to minimize the number of nuisance alarms at ports-of-entry while maximizing the ability to detect the targeted sources. Since EW will discriminate against many NORM-like radiation signatures, it should always be used in conjunction with a gross-count threshold (albeit set at a higher threshold) to ensure alarm capability on very active signatures regardless of the energy distribution.

The studies in this paper were narrowly focused to investigate the benefits of EW with regard to NORM discrimination. Emphasis has been placed on ensuring detection of SNM and more investigation is required for other targeted material. The other major category of nuisance alarms, persons with radiopharmaceutical treatments, has not been reported here. Because gamma-emission spectra from this category of sources are mostly

Fig. 13. Results from a measurement with 2 kg of DU walked through an RPM, displayed as the standard deviations above or below zero (sigma value) in four EW ratios versus sample number (time).
in the low-energy region, EW does not discriminate radiopharmaceuticals from SNM. Applications outside of commercial cargo screening, such as screening packages, or large area searches with mobile vehicles may also benefit from the EW technique.

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