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Impact of spectral smoothing on gamma radiation portal alarm probabilities

T. Burr [a,*], M. Hamada [a], N. Hengartner [b]

[a] Statistical Sciences, Los Alamos National Lab, Los Alamos, NM 87545, USA
[b] Information Sciences, Los Alamos National Lab, Los Alamos, NM 87545, USA

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ABSTRACT

Gamma detector counts are included in radiation portal monitors (RPM) to screen for illicit nuclear material. Gamma counts are sometimes smoothed to reduce variance in the estimated underlying true mean count rate, which is the “signal” in our context. Smoothing reduces total error variance in the estimated signal if the bias that smoothing introduces is more than offset by the variance reduction. An empirical RPM study for vehicle screening applications is presented for unsmoothed and smoothed gamma counts in low-resolution plastic scintillator detectors and in medium-resolution NaI detectors.

1. Introduction and summary

Data from passive radiation portal monitors (RPMs) have been collected at various ports of entry since 2002 (Geelhood et al., 2004). The main purpose is to detect potentially harmful radioactive cargo (special nuclear material, SNM) that emits gamma rays (coarsely binned into low or high energy counts) and/or neutrons. In the data we analyze, each vehicle slowly passes by a set of fixed radiation sensors, resulting in a profile time-series measurement from each sensor. The most common sensor configuration is both a driver's and passenger's side top and bottom panels, each having a neutron count and a low- and high-energy gamma counts recorded every 0.1 s during the vehicle profile. This results in a total of 12 counts (3 counts from each of the 4 panels) every 0.1 s. A few sites have also deployed NaI detectors that record gamma counts in each of 512 energy bins every 0.1 s (see Section 6). Because vehicle speeds vary, the lengths of vehicle profiles vary from approximately 20–300 counts, representing 2–30 s. For plotting and some analyses, profiles are aligned (stretched or shrunk) to a representative length, such as 150 (LoPresti et al., 2006; Gattiker and Burr, 2009; Shokair and Estrada, 2006).

Detection of illicit SNM using passive detectors is complicated by several factors, such as varying background over time at a given screening location and between locations, the wide range of shielding arising from the vehicle, cargo, and source SNM itself that characterize threat scenarios, and naturally occurring radioactive material (NORM). Vehicle self-shielding implies that vehicles with or without radioactive material will suppress the natural background, which typically arises mostly from the asphalt, concrete, air, and rock near the RPM. Self-shielding depends on the site, vehicle characteristics, and sensor location (LoPresti et al., 2006). This paper focuses on gamma counts, which can be significantly suppressed. The suppression complicates injection studies evaluating types and sizes of SNM sources that can be detected with high alarm probability (AP). Our main topic is the impact of spectral smoothing on gamma detector alarm probabilities. We consider smoothing time series of low-energy gamma counts and of NaI spectra time-averaged over each profile or over segments of each profile.

Gamma counts are sometimes smoothed to reduce variance in the estimated underlying true mean count rate, which is the “signal” in our context. Smoothing reduces total error variance in the estimated signal if the bias that the smoothing introduces is more than offset by the variance reduction. An empirical RPM study for vehicle screening applications is presented for unsmoothed and smoothed gamma counts in low-resolution plastic scintillator detectors and in medium-resolution NaI detectors.

Because detected gamma counts are well modeled by the Poisson distribution, the square root transform of counts y is recommended to stabilize the variance of $\sqrt{y}$ to 0.25 prior to smoothing (Box et al., 1978). The main findings are as follows. (1) Bias in spectral peaks and valleys introduced by smoothing can be mitigated with a 2-step procedure involving a multiplicative bias correction (MBC). First, use any reasonable smoother to smooth $\sqrt{y}$ and denote the first smooth of $\sqrt{y}$ as S_1. There will be bias in the peaks and valleys of S_1. Second,

* Corresponding author. Tel.: +1 505 665 7865; fax: +1 505 667 4470.
E-mail address: tburr@lanl.gov (T. Burr).

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smooth the ratio y/S_1^2 and denote the smooth as S_{MBC}. The final smooth is then $S_2 = S_1^2 \times S_{MBC}$, which is the final signal estimate. (2) Injection studies suggest that smoothing leads to a slight increase in illicit source alarm probabilities (APs) for low-resolution plastic scintillator detectors and to a modest increase in APs for medium-resolution detectors. In all cases, MBC is recommended because it does negligible harm when it is not needed and reduces bias in the peaks and valleys in S_1.

The following sections include additional background information, smoothing options, performance measures, empirical comparisons of smoothers, discussion, and summary.

2. Background

A few empirical studies (LoPresti et al., 2006; Burr et al., 2007; Runkle et al. 2005, 2006) investigate APs for various alarm rules by injecting the effects of gamma sources onto profiles of gamma counts from fielded detectors. None of these studies quantified the impact of spectral smoothing. We consider spectral smoothing of the low-energy gamma counts y and of the 512-energy NaI detector counts y time averaged over the entire vehicle profile or chosen time sections of the profile (Siciliano et al., 2005). Though we use the symbol y to denote either data type, the meaning of y will be clear from the context. Detected counts y of either data type are assumed to be well-modeled by a Poisson distribution with a mean that varies with time for low-energy plastic scintillator detectors counts or with energy for time-averaged NaI counts (Burr et al., 2010). No published studies considered the impact of smoothing either the scalar time series y from plastic scintillator detectors or the vector-valued, but time-averaged series y from NaI detectors. Candidate alarm rules for the scalar time series y considered here use either the maximum count rate, the average count rate, or the maximum of a moving scan of several successive count rates. The alarm rule for NaI detector counts y uses the Mahalanobis distance (Section 6).

Fig. 1 illustrates background suppression for transformed (by taking the square root) low-energy gamma counts $\sqrt{y}$ for one detector panel (driver's side, bottom panel) from an example vehicle profile. The square root transform applied to a Poisson-distributed y approximately stabilizes the variance to 0.25 for all mean values because the variance of a transform $f(y)$ for y having mean μ and variance μ is approximately $\{f'(x)\}^2_{x=\mu}\mathrm{var}(y) = \{1/2\sqrt{\mu}\}^2\mu = 0.25$ (Box et al., 1978). The smooth curves, each using several smoothers, clearly show suppressed counts compared with the background. Smoothers are described in Sections 3 and 4. We assume in both data sources that the background changes slowly compared with the typical profile duration, and, for our purposes, the background count rate is adequately estimated using the gamma count y during the first one second of the profile.

Without suppression, there should be no trend across the profile. Profile suppression causes a trend and can be defined qualitatively as having an average count rate that is less than the recent background count rate. The average aligned raw (unsmoothed) profile (obtained by linear interpolation to align each profile to length 150) is shown in Fig. 2 for Inspection Sites 1 (1800 profiles) and 2 (2000 profiles). There is a broad suppression minimum with a smooth rise, which is thought to result from the gap between the driver's cab and the truck's trailer (LoPresti et al., 2006). Of course, averaging over 1800 or 2000 aligned profiles results in relatively smooth profiles, as shown in Fig. 2, regardless of whether or not individual profiles are smoothed.

Fig. 3 is an example of the injected signal to be detected. The bottom plot shows a smoothed vehicle profile with the injected signal superimposed. Although our focus is signal detection, notice that vehicle suppression will impact the estimated signal. Some studies evaluated whether attempting to adjust for suppression increases APs (Burr et al., 2007; Gattiker and Burr, 2009) for candidate alarm rules for low-energy gamma counts y or for other scalar quantities, such as the ratio of the low energy gamma count to the high energy gamma count. Because adjusting for suppression has not led to dramatic increase in estimated APs, we will not consider alarm rule options that adjust for suppression.

Fig. 4 shows profiles from example of smoothed non-alarming NORM-carrying vehicles that have high count rates. These profiles did not alarm because the alarm threshold was set very high (corresponding to an almost 0 false/statistical alarm rate) to reduce the rate of nuisance alarms due to NORM. The average current NORM-based nuisance alarm rate over all profiles and all sites is close to 1%. However, for Sites 1 and 2, approximately 2% of profiles have a maximum scaled residual MSR > 5, where

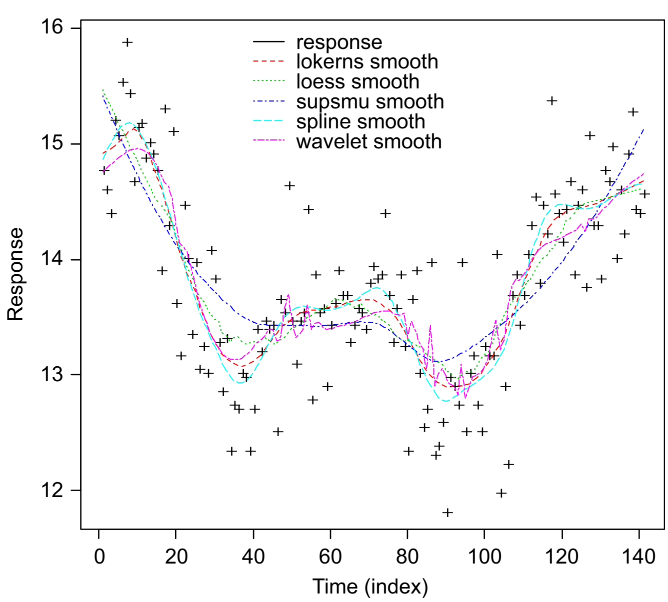

Fig. 1. Transformed ($\sqrt{y}$) low-energy raw and smoothed gamma counts versus time for a one-vehicle profile.

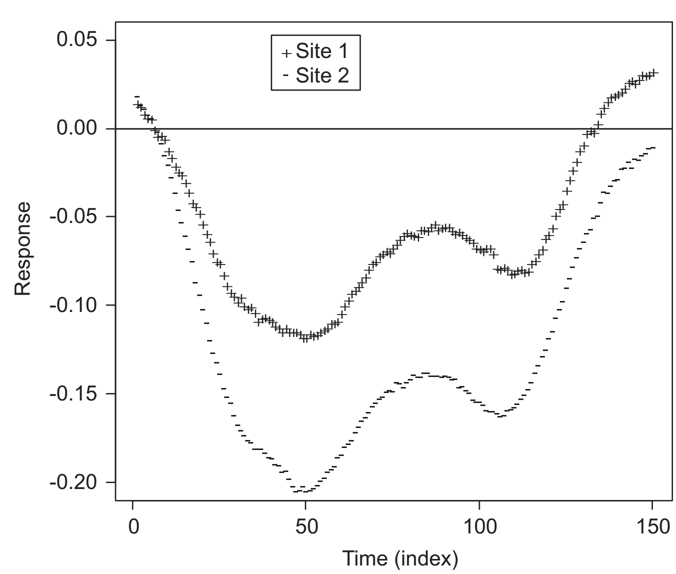

Fig. 2. The average relative change from baseline of profiles aligned for length 150 over 1800 profiles from Site 1 and 2000 profiles from Site 2.