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Improvements in the method of radiation anomaly detection by spectral comparison ratios

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HIGHLIGHTS

- We discuss enhancements to the method of spectral comparison ratios (now called Nuisance rejection Spectral Comparison Ratio Anomaly Detection, or N-SCRAD).
- Test statistics and spectral regions of interest are now optimized with simulated annealing (SA).
- The automated determination of parameters with SA enables training of the algorithm on a large, spectrally diverse threat basis.
- Estimates of the covariance of the spectral comparison ratios are now corrected for sudden changes in the total count rate of background.
- The covariance correction enables a greater sensitivity to targets and/or a reduction in false positive rates.

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ABSTRACT

We present a new procedure for configuring the Nuisance-rejection Spectral Comparison Ratio Anomaly Detection (N-SCRAD) method. The procedure minimizes detectable count rates of source spectra at a specified false positive rate using simulated annealing. We also present a new method for correcting the estimates of background variability used in N-SCRAD to current conditions of the total count rate. The correction lowers detection thresholds for a specified false positive rate, enabling greater sensitivity to targets.

1. Introduction

Gamma-ray spectroscopy has applications in many national security missions (Fagan et al., 2012), including imaging or localizing nuclear materials, and identifying constituent isotopes. Here we focus on the problem of detection during search operations, rather than – or as a precursor to – location or identification of illicit radiation sources (Runkle et al., 2009a). The problem of detecting threat signatures is compounded by difficulties, including those of estimating background radiation and supplying useful information to search operators. In most cases, the detection algorithm must be tailored before use to maximize its power to detect items of interest in a few broadly defined classes of radiation sources while reducing or constraining the rate of false positives.

The detection problem is one of separating expected and unexpected samples of, or contributions to, observed spectra. Aage et al., (1999) discussed the application of noise adjusted singular value decomposition (NASVD) to the detection and mapping of low levels of ^{137}Cs contamination from the Chernobyl accident. Their approach was to use a linear combination of principal components to estimate the contributions to observations from abnormal ^{137}Cs sources and from ordinary statistical noise, ^{40}K, U-series, Th-series sources. They applied a similar approach to the analysis of data collected by a car-borne NaI(Tl) detector, together with a visualization method to help operators identify targets (Aage and Korsbech, 2003). Guillot (2001) developed a filtering method of analyzing spectrum profiles for peaks. Energy windows were then examined for the presence of radioisotopes – both naturally occurring and presumed manmade. Hjerpe and Samuelsson (2006) examined vehicle-borne data for spectral indications of, and distances to, target ^{137}Cs sources. They used a

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energy windowing method that corrected counts observed in a ^{137}Cs window for background counts observed in a ^{40}K window, and applied a curve fit to the temporal profile of collected counts to estimate distance to the target. None of these early approaches considered the problem of estimating the confidence level or statistical significance to assign to a presumed spectral abnormality, or how to decide if an alarm or alert level had been crossed in a search operation.

From 2006 through 2010 we developed what we now call “Nuisance rejection spectral comparison ratio anomaly detection” (N-SCRAD) for flagging non-background gamma ray spectra collected from medium-resolution detectors during searches for illicit nuclear materials (Pfund et al., 2007; Anderson et al., 2008; Jarman et al., 2008; Pfund et al., 2010; Runkle et al., 2009b). The algorithm was developed for use in mobile searches, with detectors either mounted in vehicles or carried by people on foot. N-SCRAD combines exponentially weighted moving average (EWMA) tracking of expected background with a shape-based comparison of observations to the expected background to identify anomalies. Because the ability to resolve peaks from threat contributions is limited, we reduced spectra to counts collected in a few broad spectral regions of interest (ROIs). In N-SCRAD we do not apply a model for the spectral signatures of threats. However, we do choose ROIs in an attempt to maximize the sensitivity of the algorithm to prospective threats while minimizing sensitivity to benign radiation. The anomaly metrics (called alarm test statistics in this work) developed from count rates in ROIs conformed fairly well to a known chi-distribution, if the data were from background sources, and so the significance level of an observation yielding a large metric was also fairly well known as discussed below. In the intervening years we have continued to refine the algorithm, as we applied it to practical problems. The purpose of this paper is to describe those improvements.

Recently, other approaches to detecting anomalous spectral radiological signatures in low-count search and unattended monitoring scenarios have been studied. Reinhart et al. (2014) incorporated spectral comparison ratios into a spatial anomaly mapping system (SCRAM) based on mobile detectors spread over a wide area, and modified the estimation of expected variation to allow for very limited prior measurements. Chan et al. (2014) presented a non-parametric approach that allows for deviations of background counts from assumed Poisson distributions, using the concept of a Brownian Bridge. Research continued to advance in fundamental areas, including assessing the information content of spectra as a function of detector resolution (Nelson et al., 2011; Jordan et al., 2011) and displaying of information to search operators (Kock et al., 2010). Yet improvements still need to be made in the fundamental areas of detection alarm test significance and power, particularly in applications with highly variable radiation backgrounds.

Two particular problems are addressed in this paper – the first, constructing sensitive tests in the face of possible uncertainty in the threat signatures; the second, reducing false positives in the face of unanticipated, sudden changes in the radiation background. With regard to the first problem, in some cases the space of threats may include only a few items with known spectral signatures. In other cases, search operators may have much less knowledge of likely spectra from threat objects. Unanticipated sudden background changes can have operational consequences. Gradual changes can be tracked with a temporal filter, such as EWMA. Sudden changes in the shape of background spectra can often be ignored provided they are caused by changes in the relative abundance of naturally occurring radioactive materials (NORM). Unanticipated large changes in background total count rate, when coupled with even minor changes in spectrum shape or noise can trigger false alarms. In a search operation such alarms can be a significant diversion, as will be illustrated in Section 6 below.

High values of the N-SCRAD test statistics generate alarm or alert indications for search operators. Each such test statistic was a covariance-weighted length of a vector of spectral comparison ratios (SCRs), with each ratio being determined from counts collected in a pair of spectral regions of interest. The placements of the regions were engineered to collect counts from potential targets that were significantly different than the background variability likely to be observed in a search operation. We presented one method for optimizing such placements in our early work and illustrated its application assuming targets represented by ^{133}Ba and depleted uranium (DU) spectra (Pfund et al., 2007). However, in a typical application we may have many more than two representative threat surrogates, and it is likely that a single test statistic is inadequate for detecting all of them. In Section 2 of this work we present our latest, improved method for determining regions of interest and related detection algorithm parameters. The problem of determining parameters in detection algorithms in a general way was addressed by Portnoy et al. (2011) who applied a genetic algorithm. They were primarily interested in finding optimal alarm thresholds or alert levels based on measured benign source data. Our task here is one of clustering of threat spectra into groups and assigning of ROIs to the groups, for which we apply simulating annealing. Our objective function is based on estimates of minimal detectable count rates.

Key to the good performance of N-SCRAD was the development of alarm test statistics such that those resulting from benign or background spectra appeared with frequencies described by chi-distributions (Pfund et al., 2007, 2010). One step towards that goal was the elimination of long-tail, nuisance source events that can trigger false positive alarms. The most frequent of such events are triggered by the passage of naturally occurring radioactive material (NORM). In N-SCRAD, indicated anomalies in observed spectra caused by changes in NORM abundance are screened out. The algorithm can be configured to filter out other nuisance source signatures – such as those from medical isotopes or industrial sources – as needed for the search application.

Another step in obtaining predictable test statistics for benign sources is their proper standardization. Originally, N-SCRAD test statistics presented to operators during a search were standardized by covariance estimates made from previously collected background spectra with an EWMA routine. We have recently found that estimates made from past background conditions were not always good predictors of the covariance at current search conditions. Large, unanticipated changes in background radiation level often resulted in false positive detections using N-SCRAD, triggered by jumps in the alarm test statistics at background changes. In Section 5 of this work we present a correction to the covariance estimated by EWMA that improves the performance of the detection algorithm.

2. N-SCRAD optimization by simulated annealing

In N-SCRAD we used several test statistics to trigger alarm or action events. Each test was tailored to particular classes of radionuclides. In our earlier work we envisioned HEU-like, DU-like and Pu-like classes of special nuclear materials (SNM) (Pfund et al., 2010). We assigned threat surrogate materials to these classes, or “threat clusters” manually and used an optimization routine to determine spectral regions of interest (ROIs) for each cluster. Areas for improvement included optimizing the number of test statistics and ROIs, developing a formal notion of spectral similarity to automate the clustering of threat spectra, and including a broad range of radiological threat spectra, SNM spectra, with shielding