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Automated detection of radioisotopes from an aircraft platform by pattern recognition analysis of gamma-ray spectra

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ABSTRACT

A generalized methodology was developed for automating the detection of radioisotopes from gamma-ray spectra collected from an aircraft platform using sodium-iodide detectors. Employing data provided by the U.S Environmental Protection Agency Airborne Spectral Photometric Environmental Collection Technology (ASPECT) program, multivariate classification models based on nonparametric linear discriminant analysis were developed for application to spectra that were preprocessed through a combination of altitude-based scaling and digital filtering. Training sets of spectra for use in building classification models were assembled from a combination of background spectra collected in the field and synthesized spectra obtained by superimposing laboratory-collected spectra of target radioisotopes onto field backgrounds. This approach eliminated the need for field experimentation with radioactive sources for use in building classification models. Through a bi-Gaussian modeling procedure, the discriminant scores that served as the outputs from the classification models were related to associated confidence levels. This provided an easily interpreted result regarding the presence or absence of the signature of a specific radioisotope in each collected spectrum. Through the use of this approach, classifiers were built for cesium-137 (^{137}Cs) and cobalt-60 (^{60}Co), two radioisotopes that are of interest in airborne radiological monitoring applications. The optimized classifiers were tested with field data collected from a set of six geographically diverse sites, three of which contained either ^{137}Cs, ^{60}Co, or both. When the optimized classification models were applied, the overall percentages of correct classifications for spectra collected at these sites were 99.9 and 97.9% for the ^{60}Co and ^{137}Cs classifiers, respectively.

1. Introduction

The ability to identify ground sources of radioisotopes from an airborne platform presents both useful capabilities as well as unique challenges. Determining that a specific radioisotope is present at a hazardous location can give insight regarding the nature of the hazard, offer important information for use in hazard management, and help determine the origin of the event being monitored (IAEA, 2003a). Airborne monitoring is particularly suited to surveying large areas to identify radioactivity from anthropogenic sources, thereby helping to define the boundaries of a contaminated site. Recent examples of the application of airborne radiation monitoring have included the use of gamma-ray spectrometers mounted on unmanned aerial vehicles (UAVs) to map contaminated areas surrounding the Fukushima Daiichi nuclear power plant in Japan, as well as legacy uranium mines in England (Connor et al., 2016; Martin et al., 2015; Sanada and Torii, 2015).

Remotely detecting specific radioisotopes in near real-time from an airborne platform presents several challenges. Operational concerns include the need for rapid interpretation of the large quantities of data acquired in an aerial survey, the hazards and logistical challenges of field experimentation related to methods development, and the expense of operating an appropriately equipped aircraft (Burr and Hamada, 2009; Huo et al., 2014; IAEA, 1991, 2003a; Owsley et al., 2010; Portnoy et al., 2011). False detections (false positives) and a lack of sensitivity have also been problems that have plagued efforts to detect specific radioisotopes reliably from the air (Burr and Hamada, 2009). These sensitivity limitations have been one of the motivations for the increased interest in the use of UAVs for airborne monitoring, as these vehicles can typically fly lower and slower than conventional manned

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aircraft (Connor et al., 2016), thereby facilitating the integration of larger gamma-ray signals.

In our view, a practical solution to addressing the challenges noted above has four key components: (1) automating the data interpretation step to provide near real-time feedback to the analyst (e.g., within seconds to minutes), (2) associating a level of confidence with each positive isotope-specific detection, (3) maximizing the extraction of information from the acquired gamma-ray spectra, and (4) developing a procedure to simulate isotope-specific gamma-ray spectral signatures to eliminate the need to measure actual radioactive sources in the field. This paper describes the development of signal processing and multivariate pattern recognition methodology that meets these requirements.

2. Material and methods

2.1. Overview

The data analysis approach taken here was the coupling of digital filtering and nonparametric linear discriminant analysis to produce classification models (classifiers) that could be used to judge the presence or absence of the gamma-ray spectral signatures of specific radioisotopes. Novel features of this work include the development of confidence models to allow the output from the classification models to be associated with the percent probability of a correct detection. In addition, a data synthesis procedure was used to generate synthetic gamma-ray spectra for the purpose of defining the spectral components associated with a positive isotope-specific detection. The resulting spectra were used to train classification models. A conceptually similar procedure has been successfully used with passive infrared remote sensing data (Wan and Small, 2011).

This approach to gamma spectral analysis does not include the use of spectral stripping techniques (Aage et al., 2006; Furr et al., 1968). Spectral stripping has been widely used to remove interfering signals from gamma-ray spectra, but often requires prior knowledge of the site being monitored and the natural isotopes present. Thus, it can be difficult to apply in an automated way in near real time. The methodology presented here replaces the traditional spectral stripping step with a combination of digital filtering and multivariate pattern recognition, both of which can be applied in an automated manner.

In this paper, the methodology described above was used to develop classification models for two radioisotopes, cesium-137 (^{137}Cs) and cobalt-60 (^{60}Co). These radioisotopes are of interest in environmental monitoring applications because of their potential for being lost or stolen (^{60}Co) or their possible release in the event of nuclear power plant accidents (^{137}Cs). As an example, ^{137}Cs contamination will be present at the sites of the Chernobyl and Fukushima nuclear plant accidents for about 300 years due to the 30-year half-life of this radionuclide (NEA, 2002). The developed ^{60}Co and ^{137}Cs classification models were tested with field data collected under both controlled conditions and at a location in which 1960's-era nuclear weapons testing produced contamination that is still present today.

2.2. Equipment

The gamma-ray spectral data employed in this research were provided by the U. S. Environmental Protection Agency Airborne Spectral Photometric Environmental Collection Technology (ASPECT) program (Cardarelli et al., 2015). In 2010, the ASPECT aircraft was an Aero Commander 680 fixed wing aircraft. It was equipped with two RS-500 Radiation Solutions gamma-ray spectrometer units (Radiation Solutions, Inc., Mississauga, ON), combined together for a total of eight 2 × 4 × 16 inch (16.7 L) thallium-activated sodium iodide scintillation crystals. Each crystal was connected to a 1024 multichannel analyzer (2.98 keV per channel). In 2014, the ASPECT technology was moved into a Cessna 208B Caravan which was equipped with three RS-500 Radiation Solutions gamma-ray spectrometer units for a total of 12 2 × 4 × 16 inch (25 L) thallium-activated sodium iodide scintillation crystals. Other detectors were also installed but were not used in acquiring the data presented here. During the data acquisition, altitudes above ground level (AGL) were determined by use of a radar altimeter mounted on the aircraft.

The ground area interrogated by each spectrum can be approximated by consideration of the data acquisition rate (1 spectrum/s), the average ground speed of the aircraft (~50 m/s), and the typical aircraft altitude (~100 m AGL) during the data collection runs. At a fixed position of the aircraft, Duval et al. have modeled the circle of investigation (COI) of the spectrometer as a function of a number of parameters (Duval et al., 1971). For altitudes of ~100 m AGL, the radius of the COI for an integral of 50% of the source yield was modeled to be approximately equal to the aircraft altitude (i.e., ~100 m for the data described here). Considering each acquired spectrum to be the result of viewing a series of overlapping circles whose centers span the 50 m traveled during one scan, the area interrogated was approximately elliptical in shape with a diameter of ~250 m along the flight track and ~200 m perpendicular to the flight track. While each acquired spectrum interrogated a relatively large area, radioactive sources at a target location could be pinpointed to within a few meters by flying a grid search pattern in which the individual lines of the grid were 15–30 m apart.

Data sets were derived from overflights of either (1) controlled sites at which commercial ^{137}Cs and ^{60}Co sources (activities of tens to hundreds of megabecquerels) were placed at known locations on the ground, (2) a location known to contain contamination from the Sedan nuclear weapon test, or (3) a nuclear power plant. The Sedan test was a shallow underground nuclear test (104 kT) conducted in July 1962 as part of Operation Plowshare, a program to investigate the use of nuclear weapons for civilian purposes. Data collected with both ASPECT platforms were used together in the work described below.

Gamma-ray spectra collected in the laboratory were also used in this work. The instrumentation employed was a Radiation Solutions RS-500 spectrometer similar to that described previously but comprising a single 4 × 4 × 16 inch crystal rather than the large multi-unit array employed in the aircraft. The data collected in the laboratory were obtained by taking measurements of controlled radioactive sources at varying distances from the detector.

The computational work described here was performed with a custom-built computer utilizing two Xeon E5-2680 v2 10(20) core processors (Intel Corp., Santa Clara, CA) running at 3.6 GHz. This computer operated under Red Hat Linux (Version 6, Red Hat, Inc., Raleigh, NC). Software utilized in this research included in-house programs written in Fortran and compiled with the Intel Fortran Compiler (Version 10.0.023, Intel Corp.), in-house Linux shell scripts, MATLAB (The MathWorks, Natick, MA), Google Earth (Google, Inc., Mountain View, CA), ENVI/IDL (Exelis, Inc., Boulder, CO), and Origin Lab Pro 9 (OriginLab Corp., Northampton, MA).

2.3. Assembly of training set

The supervised pattern recognition methodology used in this work required the definition of a training set of known “analyte-active” and “analyte-inactive” spectra. The terms, analyte-active and analyte-inactive, denote, respectively, the cases in which a spectrum contains the signature of the specific radioisotope of interest (^{137}Cs or ^{60}Co) or does not contain the signature.

Pure-component spectra of ^{137}Cs and ^{60}Co are characterized by photopeaks near 662 keV for ^{137}Cs (technically this gamma ray is emitted from barium-137, the decay product of ^{137}Cs, but is traditionally associated with ^{137}Cs) and 1173 and 1333 keV for ^{60}Co. Pure-component spectra were collected by placing a known radioactive source in various proximities to the detector. The data were accumulated at one scan per second and were subsequently co-added. The pure-component spectra were used in the generation of synthetic spectra that

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