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Improved radiological/nuclear source localization in variable NORM background: An MLEM approach with segmentation data ☆

Robert D. Penny [a,*], Tanya M. Crowley [a,1], Barbara M. Gardner [a], Myron J. Mandell [a], Yanlin Guo [a], Eric B. Haas [a], Duane J. Knize [a], Robert A. Kuharski [a], Dale Ranta [a], Ryan Shyffer [a], Simon Labov [b], Karl Nelson [b], Brandon Seilhan [b], John D. Valentine [c,2]

[a] Leidos Inc., 10260 Campus Point Road, San Diego, CA, USA
[b] Lawrence Livermore National Laboratory, Livermore, CA, USA
[c] Lawrence Berkeley National Laboratory, Berkeley, CA, USA

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ABSTRACT

A novel approach and algorithm have been developed to rapidly detect and localize both moving and static radiological/nuclear (R/N) sources from an airborne platform. Current aerial systems with radiological sensors are limited in their ability to compensate for variable naturally occurring radioactive material (NORM) background. The proposed approach suppresses the effects of NORM background by incorporating additional information to segment the survey area into regions over which the background is likely to be uniform. The method produces pixelated Source Activity Maps (SAMs) of both target and background radionuclide activity over the survey area. The task of producing the SAMs requires (1) the development of a forward model which describes the transformation of radionuclide activity to detector measurements and (2) the solution of the associated inverse problem. The inverse problem is ill-posed as there are typically fewer measurements than unknowns. In addition the measurements are subject to Poisson statistical noise. The Maximum-Likelihood Expectation-Maximization (MLEM) algorithm is used to solve the inverse problem as it is well suited for under-determined problems corrupted by Poisson noise. A priori terrain information is incorporated to segment the reconstruction space into regions within which we constrain NORM background activity to be uniform. Descriptions of the algorithm and examples of performance with and without segmentation on simulated data are presented.

1. Introduction

A Government funded program, known as Airborne Radiological Enhanced-sensor System (ARES), is underway to improve the detection and localization of radiological sources from an airborne platform. The hardware system being developed by Leidos Inc. is known as HeliSORDS and will be reported separately. Here we report the reconstruction algorithms to process the data stream from the HeliSORDS instrument.

Radiation detection from a moving baseline is challenging because variations in the concentration of naturally occurring radioactive materials (NORM) can mask the faint signatures from radiological and nuclear (R/N) threat sources. It has been demonstrated that simply increasing the area of the detectors does not yield a commensurate increase in detection capability [1]. Coded-aperture imaging techniques have been employed to separate distributed background sources from compact threat sources and we have employed such an approach in a previous land-based system known as the StandOff Radiation Detection System (SORDS) [2].

Weight is at a premium in an airborne instrument and HeliSORDS does not utilize a coded aperture with the dead weight of a passive shadow mask. Instead, the instrument employs an active mask, where the scintillation detectors are arranged so their mutual cross-shadowing provides directionality information perpendicular to the track. Source localization information along the flight track is primarily determined by proximity.

Events that are two-way coincident between detectors are also extracted. The arrival trajectory of these gamma photons can be determined with greater specificity using the known energy-angle relationships of Compton-scattering. This information will be

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* Corresponding author.
E-mail address: robert.d.penny@leidos.com (R.D. Penny).
[1] Principal corresponding author.
[2] Formally at Leidos.

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incorporated in the reconstruction by including forward probability models for these processes in the system matrix.[3]

The reconstruction algorithm we have developed combines these information sources using an isotope-spatial MLEM approach to solve for source activity maps. The forward model is the full isotope-spatial model as described by Wahl [4] and consists of a system matrix which transforms a pixelated survey region of emission sources to detector responses. In our case we determine the detection probabilities and responses through GEANT[4] simulations. These are performed at a number of discrete irradiation energies and angles. Analysis code then extracts features such as full-energy peak, Compton edge, backscatter peak and continuum response regions in the detector response. These features are subsequently used as parameters in interpolation code to predict the forward response at intermediate energies and angles in a computationally efficient manner.

A goal of the program is to locate threat sources on a single survey pass and not require a "crop-dusting" flight pattern. Simulations demonstrate that this is achievable solely by using the active-mask and proximity information. Notwithstanding this, the reconstruction space has many degrees of freedom compared with those available in the measurement data. We have investigated a technique where we reduce the required degrees of freedom in the solution by incorporating a priori information to segment the ground underneath into regions within which we would anticipate the NORM background to be relatively uniform. This allows us to collapse multiple pixels on the ground into a reduced number of segments within each of which we allocate uniform background radionuclide activity. The target threat radionuclide's reconstruction space is not segmented and is still dispatched to a pixelated source activity map (SAM).

During actual radiation survey flights we will utilize the Government-owned Zones of Protection (ZoP) database to segment the ground below.[5] While background radiation is unlikely to be perfectly uniform within segments derived from ZoP, the improvements in the reconstruction that result from a reduction in the degrees of freedom in the reconstruction space may more than make up for problems caused by these discrepancies. This will be tested in the near future with actual flight data. In simulations, with perfect alignment between the segmented background source activity that we simulate on the ground, and the segmentation of the background reconstruction SAMs into which we reconstruct, we have noticed a dramatic reduction of bleed through from the background radiation into the threat reconstruction of SAM. This is demonstrated later.

2. Detector hardware

The detector system contains four arrays, two per helicopter pod (Fig. 1), with each array containing twenty three $2.5 \times 2.5 \times 42\ \mathrm{cm}^3$ cesium-iodide detector logs. These are placed such that each detector's response to radiation incident on a 4π sphere is spatially modulated by shading from other detectors.

Scintillation light in each detector is captured by a pair of photomultiplier tubes (PMTs) placed at opposite ends of each detector. This allows us to measure not only the total energy deposited by the gamma photon, but also the approximate position along the detector where it interacted. This is used in conjunction with the acquisition system's capability to detect coincidence between multiple detectors to also incorporate a Compton-imaging functionality into the detection system.

3. System model

As the airborne platform traverses the survey region, the probability that a gamma photon emitted from any individual point on the ground will be detected (on any given detector) varies as a function of atmospheric attenuation with distance, inverse square proximity effects and the orientation of the detector arrays. These couplings can all be expressed simply through Eq. (1). Here, the source vector f represents the activities of various radionuclide sources pixelated throughout the survey region; the measurement vector g represents the rate of detector events on each of the detectors as a function of platform position, detector number and measurement channel energy; and the system matrix A represents the forward probabilities that couple unit activity on each of the source components to event rates on the detectors.[6]

$$Af = g \tag{1}$$

To explain the components of Eq. (1) in more detail it is helpful to split it into component sub-blocks, as shown in Eq. (2).

The components of f represent activities of various background (f_b) and target (f_t) radionuclides on pixels covering the survey region. These activities are assumed to be constant during the course of the survey.

Each row in A multiplies the entire source activity vector f to produce a single component in the event-rate measurement vector g. Each component in g represents the rate of events measured on a given energy channel of a given detector at a given position of the airborne platform. For example, some components in a row in A would couple ^{137}Cs pixels on the ground, emitting gamma photons at 662 keV, into that detector's 662 keV measurement channel. On this same row would be other components that couple ^{40}K pixels, emitting photons at 1460 keV into that same detector's 662 keV measurement channel. These matrix elements represent the probability that emitted 1460 keV photons from that pixel will register on that detector in the 662 keV measurement channel through some combination of down-scatter or through that detector only capturing part of the arriving photon's energy. During a flight, we measure a count N for each of these components, which is assumed to be a statistically independent random variable sampled from a Poisson distribution with an underlying rate g.

Each time the platform moves, a different block of coupling coefficients in A must be calculated and different set of measured rates g come into play. Two position blocks are represented in Eq. (2); the second block starting with k added to indices of both the rows of A and the rows of the detector event rates g.

$$\begin{bmatrix} b_{1,1} & b_{1,2} & b_{1,3} & \cdots & t_{1,1} & t_{1,2} & t_{1,3} & \cdots \\ b_{2,1} & b_{2,2} & b_{2,3} & \cdots & t_{2,1} & t_{2,2} & t_{2,3} & \cdots \\ b_{3,1} & b_{3,2} & b_{3,3} & \cdots & t_{3,1} & t_{3,2} & t_{3,3} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \\ b_{k+1,1} & b_{k+1,2} & b_{k+1,3} & \cdots & t_{k+1,1} & t_{k+1,2} & t_{k+1,3} & \cdots \\ b_{k+2,1} & b_{k+2,2} & b_{k+2,3} & \cdots & t_{k+2,1} & t_{k+2,2} & t_{k+2,3} & \cdots \\ b_{k+3,1} & b_{k+3,2} & b_{k+3,3} & \cdots & t_{k+3,1} & t_{k+3,2} & t_{k+3,3} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} f_{b1} \\ f_{b2} \\ f_{b3} \\ \vdots \\ \vdots \\ f_{t1} \\ f_{t2} \\ f_{t3} \\ \vdots \\ \vdots \end{bmatrix} = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ \vdots \\ g_{k+1} \\ g_{k+2} \\ g_{k+3} \\ \vdots \end{bmatrix} \tag{2}$$

[3] A third un-imaged response modality, known as the Spectral Anomaly Alarm, has been developed by our collaborators at Lawrence Livermore National Laboratory (LLNL) and operates independently of our imaging modalities [3]. This technique detects energy spectrum anomalies after suppressing the majority of variations that occur in the NORM background.

[4] GEometry ANd Tracking developed by CERN, the European Center for Nuclear Research.

[5] ZoP has been developed jointly by Government agencies including the National Security Agency (NSA), ISR Task Force, Army G2 and the Defense Advanced Research Projects Agency (DARPA).

[6] To simplify the discussion that follows we only refer to activity placed on pixels. However tracked vehicles moving through the field of view or radon activity in the air can also be treated as "pixels" providing we have a forward probability model for the coupling of emitted radiation from this entity to the detector. In simulations we have demonstrated the ability of the algorithm to correctly assign detected radiation to a single moving vehicle carrying a threat source with multiple other vehicles tracking through the field of view.