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Communications

Advanced multi-dimensional imaging of gamma-ray radiation

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Abstract

The tracking of radiation contamination and distribution has become a high-priority U.S. DOE task. To support DOE needs, Radiation Monitoring Devices Inc. has been actively carrying out research and development on a gamma-radiation imager, RadCam 2000™. The imager is based upon a position-sensitive PMT coupled to a scintillator near a MURA coded aperture. The modulated gamma flux detected by the PSPMT is mathematically decoded to produce images that are computer displayed in near real time. Additionally, we have developed a data-manipulation scheme which allows a multi-dimensional data array, comprised of x position, y position, and energy, to be used in the imaging process. In the imager software a gate can be set on a specific isotope energy to reveal where in the field of view the gated data lies or, conversely, a gate can be set on an area in the field of view to examine what isotopes are present in that area. This process is complicated by the FFT decoding process used with the coded aperture; however, we have achieved excellent performance and results are presented here.

Keywords: RadCam2000; IMAGE2000; Radiation; Imager; Gamma Ray; MURA; Coded Aperture; Data Cube

1. Introduction

The tracking and verification of radiation sources, contamination, and distribution have become a high-priority U.S. Department of Energy tasks. To support DOE needs, Radiation Monitoring Devices Inc. has been actively involved in carrying out research on and the development of a gamma-radiation imager, RadCam 2000™ [1],[2],[3]. This device has the capability of determining radiation distribution, intensity, and energy from a distance. This is done by creating a radiation plot, via a nuclear detector, and overlaying the information upon a video image of the area being examined.

Recently, we have developed a data manipulation and storage scheme called the "data cube." The data-cube technique allows a multi-dimensional array of data comprised of x position, y position, and energy to be used in the imaging process. Gating along the different axes of the cube allows sophisticated analysis and visualization of radiation maps created by the imager.

2. Methods

2.1 System Overview

The primary components of the imager are a PSPMT, a CsI(Na) scintillator, and a tungsten,

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modified-uniformly-redundant-array (MURA), coded-aperture mask. The thin, 5 cm x 5 cm CsI(Na) scintillator is optically coupled the face of the PSPMT. The PSPMT-scintillator detector is placed 6 cm, axially centered, behind the MURA aperture. The Hammamatsu R2486 PSPMT generates 4 output signals from a position-sensitive, x-y-grid anode. These signals can be used to determine two key properties about the interaction of gamma rays with the scintillator; energy and position. The energy proportional value is generated when the 4 signals are summed in a digital or analog manner. The position value, in the x and y directions, is generated when the difference divided by the sum of two signals is taken along an edge of the grid. When the assembly is in the presence of a gamma-ray source the position information can be used to generate a 2-dimensional histogram of the shadow pattern made by the coded aperture on the detector. The histogram can be correlated with the mask pattern to yield a radiation image using a laptop computer. This mathematical decoding is carried out by computationally efficient, fast-Fourier transforms (FFT), in a near real-time manner, and when overlaid on a co-registered video image of the area undergoing examination the system can produce detailed information about isotope location, type, and intensity.

2. 2 Image Reconstruction

The "shadowgram" produced by the coded-aperture is sampled by the PSPMT, held by a PSPMT I/O card, and then stored digitally via the analog capture card as the mask intensity array, $M(i,j)$. The image is then corrected for PSPMT non-linearity and gain variations across the tube face by reference to a look-up table. For a discretely-sampled, two-dimensional image, such as that generated by the RadCam 2000™, the mask decoding pattern $D(i,j)$ can be correlated with the corrected mask-intensity array $M_c(i,j)$ to yield the reconstructed image data $R(k,l)$ as seen in Eq. (1) [4],[5],[6].

$$R(k,l) = \sum_{i=1}^{r}\sum_{j=1}^{r} M_C(i,j)D[\mathrm{mod}_r(i+k), \mathrm{mod}_r(j+l)], \qquad (1)$$

Here r is the number of apertures in the basic coded-mask MURA pattern along an edge and mod is the modulus operator. It was found, however, that the looping structure to determine $R(k,l)$ was computationally lengthy and a faster method was chosen. Since the calculations from Eq. (1) go as the number of terms squared, fast Fourier transforms (FFT) were used to reduce the calculations to the order of number of terms times the log of the number of terms. This resulted in a 35-fold improvement in processing speed and image generation. The FFT version of Eq. (1) is shown in Eq. (2),

$$R = \mathrm{FFT}[\ (\mathrm{FFT} \star\ (M_c) \cdot \mathrm{FFT}(D)\ ] \star . \qquad (2)$$

Here $\star$ is the correlation operator. The R data are displayed as the radiation image overlaid on a co-registered video image to make the radiation map.

2.3 The Data Cube

Heretofore, the general approach has been to have a mask intensity array, $M_C(i,j)$, that was strictly two dimensional. We have developed a new mask intensity array, $M_C(i,j,E_n)$ that has an added energy dependence to produce a 3-dimensional data array of depth n. The FFT of each intensity level of energy bin n allows the creation of the subsequent mathematical entity $R(i,j,E_n)$, which we call the “data cube.” The data cube is an image, $R(i,j)$, for each energy level or energy bin. Through the IMAGE software of RadCam 2000™ it is possible gate along any axis of the $R(i,j,E_n)$ array and, depending on the axis, project out a radiation image or energy spectrum.

The primary difficulty with this approach resides with the normalization of an $R(i,j,E_n)$ for a specific level relative to the $(n\text{-}1)$ others. The correlation process adds a constant offset to the image that depends uniquely on that intensity data ($M(i,j,E_n)$) that produces that image. The offset is a result of the technique used to develop the decoding matrix, $D(i,j)$, using balanced correlation and is well described in Ref. [4]. To establish the normalization constant for each level we utilize the energy spectrum that is acquired simultaneously with the intensity data during imager data acquisition runs. The energy spectrum contains the amplitude of the contribution (counts) for each energy level relative to the other levels which is also the spectral shape. The normalization constants from each level are proportional to the total counts in each image multiplied by its percentage contribution to the overall energy spectrum. The utility of this technique is presented in the next section.

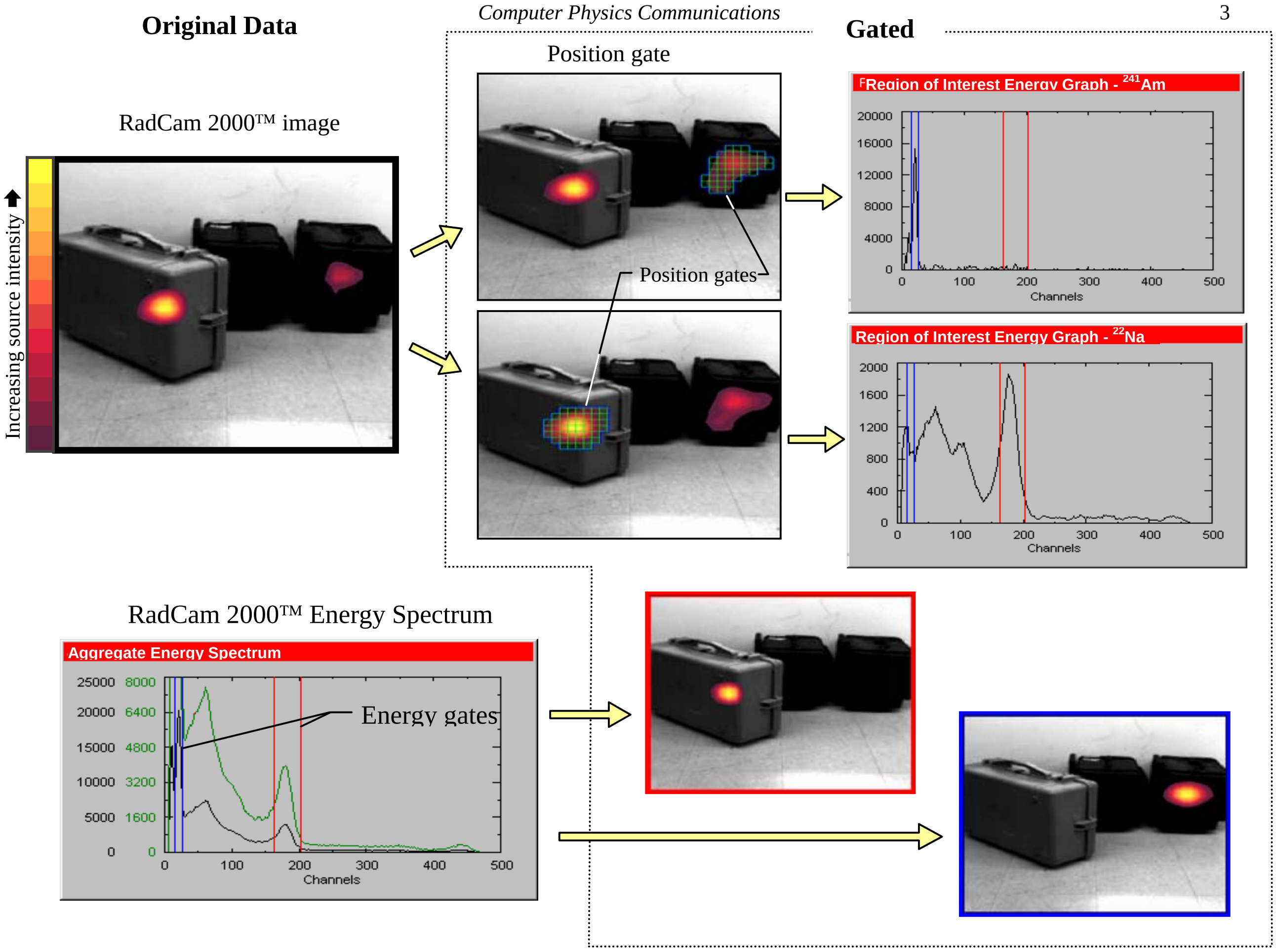

Figure 1. This figure is a visual image of the data pathway in the RadCam2000™ IMAGE software. The data on the left is the data produced at the data acquisition runtime. Data to the right is gated data generated by setting position or energy gates on the leftmost images. With the IMAGE2000 software it is possible to set a position gate (or multiple gates) to generate energy spectra specific to that area of interest. It is also possible to set energy gates, as shown in the lower left energy spectrum, to generate position images specific to that energy band. In this example a 100 µCi ^{241}Am source is in the right (black) case and a 100µCi ^{22}Na source is in the gray suitcase to the left. The main image was acquired, in a count-based mode, for one million counts using a coded-aperture, image/anti-image technique.

3. Results

3.1. Data Cube

To demonstrate the effect of the data cube on radiation imaging, a series of images are given in Fig. 1. There are three suitcases in the image. The leftmost suitcase has a 100 µCi ^{22}Na source (511 and 1274 keV gamma rays) in it and the right most suitcase has a 100µCi ^{241}Am source (25 and 60 keV gamma rays) in it. The image and graph to the left of Fig. 1 are the data acquired during a RadCam 2000™ data acquisition run. The image was acquired for an aggregate total of one million counts using a coded aperture image/anti-image procedure [1]. Two radiation sources labelled in a purple-to-yellow intensity-color scheme are clearly discernable when a 30% threshold is used to reduce backgound image contributions. Post data acquisition, if a position gate is placed around a source, as shown in two of the top right images, energy spectra related to that area of the image can be generated. In this case the topmost graph clearly shows the gate around the right source produces the energy spectrum of ^{241}Am and below that, the gate around the left source is the ^{22}Na source. These procedures correspond to gating along the energy axis in the data cube. If data-cube gating parallel to the image planes is carried out, or a gate in the energy spectrum is made, images can be produced corresponding to that energy region. This is shown in Fig. 1 lower right, where an energy gate around the ^{241}Am gamma-ray peak yields the ^{241}Am radiation image and a gate around the ^{22}Na photopeak yields the ^{22}Na radiation image.

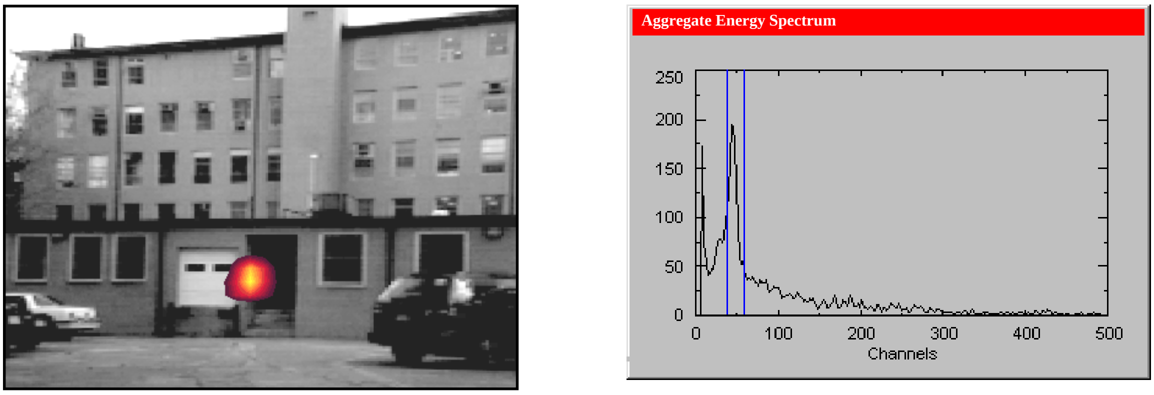

Figure 2. A RadCam 2000™ image of a 20 mCi ^{57}Co source (122 keV gamma rays) on a lab bench of interior room. Imaged from 70 m in 5 minutes. The blue lines in the energy spectrum centered around the 122-keV gamma-ray line in the ^{57}Co spectrum produce the image above.

3.2. Advanced Applications

The RadCam2000 radiation imaging device has been designed, primarily, for DOE decontamination and decommissioning (D&D) activities. An example of the effectiveness of the gating and noise reduction procedures possible with the data cube, are demonstrated in an additional radiation image made using the imager. A 5-minute image of a 20 mCi ^{57}Co source (122 keV gamma rays) is shown in Fig. 2. The radiation source in this image is placed inside the building on a lab bench of an interior room approximately 70 m from the imager. As demonstrated by the image, the source is easily located within the imager field of view. However, this image is derived from the gated photopeak in the aggregate energy spectrum to the right. An image produced with no gate (not shown) does not uniquely identify the source location.

4. Conclusions

The multi-dimensional gating techniques are very powerful for extracting information from radition images generated by the RadCam 2000™ imager. In fact, in most cases the energy-gating technique enables the location of sources that would otherwise go undetected. Position gating techniques are excellent for determining the distribution of specific types of isotopes in a given image. Current applications include the use of imager for tracing isotope holdup at a gaseous diffusion plant [7] and the tracking of Plutonium in a high-throughput dissolver system on a dynamic basis [8]. Future work will focus on establishing a fourth dimension to the data cube, time. The ability to gate on the time variable would have profound utility in temporal source tracking.

5. References

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