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CONF-840531--3

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SUBMITTED TO: 6th Annual ESARDA Symposium
Venice, Italy
May 14-18, 1984

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A SYSTEM FOR IMAGING PLUTONIUM THROUGH HEAVY SHIELDING*

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Abstract

A single pinhole can be used to image strong self-luminescent gamma-ray sources such as plutonium on gamma scintillation (Anger) cameras. However, if the source is weak or heavily shielded, a poor signal to noise ratio can prevent acquisition of the image. An imaging system designed and built at Los Alamos National Laboratory uses a coded aperture to image heavily shielded sources. The paper summarizes the mathematical techniques, based on the Fast Delta Hadamard transform, used to decode raw images. Practical design considerations such as the phase of the uniformly redundant aperture and the encoded image sampling are discussed. The imaging system consists of a custom designed m-sequence coded aperture, a Picker International Corporation gamma scintillation camera, a LeCroy 3500 data acquisition system, and custom imaging software. The paper considers two sources--1.5 mCi ^{57}Co unshielded at a distance of 27 m and 220 g of bulk plutonium (11.8% ^{240}Pu) with 0.3 cm lead, 2.5 cm steel, and 10 cm of dense plastic material at a distance of 77.5 cm. Results show that the location and geometry of a source hidden in a large sealed package can be determined without having to open the package.

1. Introduction

A single pinhole can be used to image strong, self-luminescent gamma-ray sources such as plutonium on gamma-ray scintillation (Anger) cameras. However, if the source is weak or heavily shielded, a poor signal to noise ratio can prevent acquisition of the image. An imaging system has been designed and built at Los Alamos that uses a coded (multihole) aperture that can image heavily shielded sources. The aperture is a uniformly redundant array based on a tenth-order m-sequence containing 1023 elements. This aperture was chosen to be compatible with the Fast Delta Hadamard transform decoding technique. The Hadamard transform technique is used to decrease greatly the computational difficulties normally associated with the decoding of coded aperture images.

2. Coded Aperture Imaging

Fenimore and Cannon[1] proposed the concept of using uniformly redundant arrays (URAs) to perform x-ray and gamma-ray imaging. A simplified mathematical development of coded-aperture imaging for planar sources that are parallel to the detector surface follows. Consider a plane detector that detects photons and let P(x,y) represent the number of photons collected at point (x,y) on the detector. Similarly let O(x,y) represent a planar source that is parallel to the detector surface that emits the photons of interest. Additionally, let A(x,y) be a multi-hole aperture that is between the source and the detector and is parallel to them both. Then

$$P(x,y) = O(x,y) * A_m(x,y) \quad , \tag{1}$$

where A_m is an appropriately magnified version of the coded-aperture array based on the geometry of the object, detector, and coded-aperture array. The amount of magnification is

$$m = (z + f)/z \quad , \tag{2}$$

where f is the distance between the coded aperture and the detector, and z is the distance from the aperture to O(x,y). Note that * is a two-dimensional correlation operator.

The imaging system acquires P(x,y); however, the desired information is the function O(x,y). Thus, O(x,y) is computed as follows:

$$O(x,y) = P(x,y) * G_m(x,y) \quad , \tag{3}$$

where $G_m(x,y)$ is an appropriately magnified decoding array computed from $A_m(x,y)$.

Cannon and Fenimore[2] showed that an m-sequence URA is often superior to other URAs since it appears to be a random pattern. Fenimore and Weston[3] show that if the coded aperture is based on m-sequences, the computational difficulties encountered in solving Eq. (3) are greatly reduced. An m-sequence is a pseudo-random sequence of ones and zeros of length n where n is equal to $2^m - 1$. Harwit and Sloan (Appendix of Ref. 4) list the generating polynomials for those sequences and show how they are generated. These sequences have special autocorrelation properties. Let $s = (s_0, s_1, \ldots, s_{n-1})$ be an m-sequence of length $2^m - 1$ where all zeros have been changed to minus ones. Then its cyclic autocorrelation function is

$$r_j = \sum_{i=0}^{n-1} s_i s_{j+i} \quad , \tag{4}$$

which gives $r_j = 2^m - 1$ for $j = 0$ and $r_j = 0$ for $j \neq 0$. All subscripts are evaluated modulo n.

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*Work performed under the auspices of the US Department of Energy, Office of Safeguards and Security.

Fenimore and Weston[3] also show that a two-dimensional image can be unfolded into a one-dimensional vector that corresponds to a one-dimensional aperture that has been unfolded in the same fashion as the image. The encoded image is formed by the summation of many images shifted in space, each one the result of a hole in the aperture. In vector form, Eq. (1) becomes

$$\eta = \psi * s \quad , \tag{5}$$

where η is a vector containing the unfolded encoded image, ψ is the unfolded source image, and s is the unfolded aperture. Equation 5 can be converted to matrix notation by building the S matrix.

$$S = \begin{bmatrix} s_{0,0} & \cdots & s_{0,n-1} \\ \vdots & & \\ s_{n-1,0} & & s_{n-1,n-1} \end{bmatrix} \quad , \tag{6}$$

where $S_{ij} = s_{i+j}$, s_{i+j} being the elements of the m-sequence. Thus, the correlation in Eq. (5) is represented by

$$\eta = S \cdot \psi \quad . \tag{7}$$

The decoded image is

$$\psi = S^{-1}\eta \quad . \tag{8}$$

Since S has shifted m-sequences for rows, the m-sequence property described in Eq. (4) causes

$$S \cdot S = \frac{1}{2^m - 1} \cdot I \tag{9}$$

where I is the identity matrix. Thus, the image ψ can be decoded by

$$\psi = \frac{1}{n} S \cdot \eta \quad . \tag{10}$$

Therefore, no matrix inversion is required. However, a naive evaluation of Eq. (10) will require roughly n^2 multiplications. It turns out that a Fast Fourier Transform solution of Eq. (10) would require roughly $(4n)\log_2(n)$ multiplications (Fenimore and Cannon[5]), whereas the Fast Delta Hadamard transform solution (Fenimore and Weston[3]) of Eq. (10) would require $(2n)\log_2(n)$ integer additions. For a tenth-order m-sequence, a 100-to-1 reduction can be achieved by using transform techniques to evaluate Eq. (10). In the case of the Hadamard transform, even greater reduction in computation time can be achieved because the operation involves addition rather than multiplication.

The fact that integer additions are involved allows one to implement the decoding algorithm on an eight-bit microcomputer such as a LeCroy 3500.

For a general review of the properties of Hadamard transforms, see Harwit and Sloan.[4]

3. Coded-Aperture Imaging

A coded-aperture imaging system with the following components has been designed and built at Los Alamos: Picker International Corporation Dynamo Camera; LeCroy 3500 Microcomputer System; LeCroy 3512 Analog-to-Digital Converters (ADCs); specially fabricated, tungsten coded aperture; and system software for acquisition and manipulation of images.

Figure 1 illustrates the main hardware components of the imaging system. Whenever the source emits a gamma ray, it either passes through a hole in the coded aperture or is blocked by the opaque part of the aperture. If it passes through the aperture, it strikes the NaI(Tl) crystal (26 cm in diam by 1.3 cm thick) causing a scintillation. The scintillation is detected by one or more of 37 photomultiplier tubes behind the crystal and is converted to electrical signals. The electrical signals are processed such that X and Y analog signals descriptive of the Cartesian coordinates of the location of the scintillation are produced along with a logic strobe Z that indicates when the X,Y signals are valid. The Picker camera can be adjusted such that strobe Z is valid for an energy window location and width determined by the user. The NaI(Tl) crystal is twice the thickness that Picker routinely installs in its cameras that are intended for medical applications. Otherwise, the Dynamo Camera is the same as a standard camera that is in routine hospital use.

The X,Y coordinate signals are each digitized into two 7-bit binary numbers by the LeCroy 3512 ADCs. Those 7-bit numbers are then formed into a 14-bit pixel address. A pixel is retrieved from an image memory, incremented by one, and replaced in the image memory. Once an image has been acquired, it can be decoded, displayed, and processed using a variety of specially written LeCroy 3500 programs.

LeCroy 3500 Microcomputer System

The LeCroy 3500 microcomputer system is based on the Intel 8085 eight-bit microprocessor. A dual-diskette subsystem supports a file-oriented operating system (CP/M) that allows use of both assembly language and Fortran programs. A built-in keyboard and video display perform the function of a terminal; hardcopy output can be made on the line printer. The LeCroy 3500 possesses a number of features that make it uniquely suited for data acquisition from and control of scientific experiments. An eight-slot CAMAC minicrate allows electrical and software interfacing to an extremely broad range of experiments. Because the 64k by 8-bit program and data memory space of the 8085 processor is inadequate for applications that produce large amounts of data, a separate 64k by 24-bit memory is available for data storage. As many as four 128 x 128 images can be stored in this data memory at one time with pixel values ranging from 0 to $2^{24} - 1$.

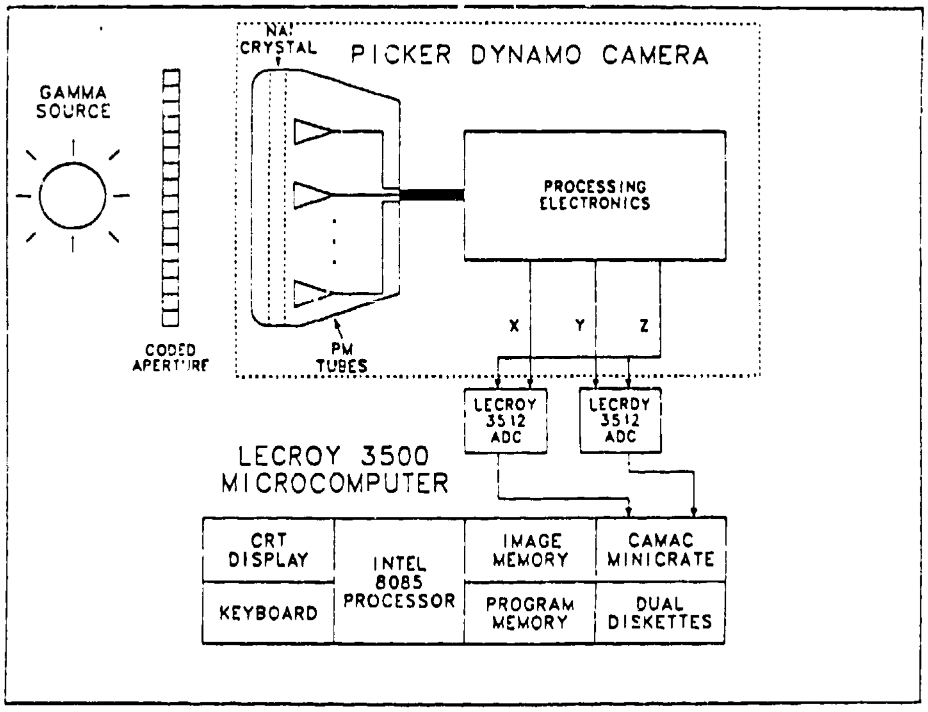

Fig. 1.
Coded-aperture imaging system.

Coded Aperture

The coded aperture was maufactured by Buckbee-Mears of St. Paul, MN. The opaque parts are made of tungsten 0.64 cm thick. The aperture consists of two cycles, both horizontal and vertical, of the mask pattern shown in Fig. 2. This pattern is a two-dimensional array containing a tenth-order m-sequence. The 10-sequence was folded into the pattern as follows: consider an array as with 31 rows and 33 columns represented by a matrix A:

$$A = \begin{bmatrix} A_{0,0} & \cdots & A_{0,32} \\ \vdots & & \\ A_{30,0} & & A_{30,32} \end{bmatrix} \quad (11)$$

The array is opaque if $s_i = -1$ and not opaque if $s_i = 1$. The A_{ij} are calculated as follows:

$$A_{jk} = s_i \quad , \quad (12)$$

where $j = i_{\mathrm{mod}\ 31}$ and $k = i_{\mathrm{mod}\ 33}$. Equation (12) describes "snaking" the m-sequence into the pattern in a diagonal fashion wrapping to the opposite side when a boundary is reached. Several possible foldings of the m-sequence can be used to construct an aperture; however, Fenimore and Weston[2] show that the method described in Eq. (12) is superior to others because the pattern produced is periodic. The actual dimensions of the pattern shown in Fig. 2 are 13.3 by 12.5 cm with each element in the array 0.40 by 0.40 cm. The actual size of the total aperture is 28 by 26.3 cm.

From theory one might expect that the phase of the URA is unimportant, that is, one could start the one-dimensional m-sequence anywhere within the two-dimensional aperture pattern. All nearly square URAs apparently have one row which is either all holes or all opaque. The remaining rows are approximately half holes and half opaque. The completely filled row can interact with distortions in the system to produce artifacts. Distortions can be due to practical considerations such as a detector background that varies from one side of the detector to the other or an aperture fabrication problem such that the holes on one side of the aperture are slightly larger than on the other side. In these cases, a crossed-shaped artifact will

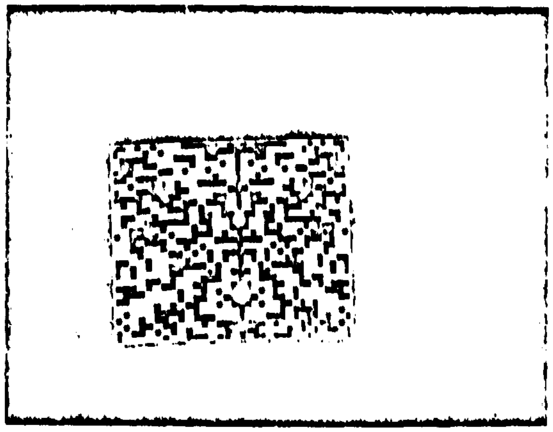

Fig. 2.
Aperture pattern for tenth-order m-sequence.

occur in the decoded image due to the presence of the completely filled row. The solution to these practical considerations (Fenimore[6]) is to place the completely filled bar in the center of the aperture pattern as shown in Fig. 2. Fenimore[6] gives generating polynomials and starting seeds to generate URA apertures with the bar in the center.

Imaging Software System

A comprehensive set of imaging acquisition and processing programs have been written to enable the LeCroy 3500 to acquire and decode coded aperture images. Nine functions are performed on images:

- acquisition of a raw image,
- centering of a raw image,
- rotation of a raw image,
- difference image of two images,
- scaling an image,
- interpolation of a raw image,
- decoding the interpolated image,
- display of an image, and
- storage and retrieval of images.

The major functions are discussed below.

Image Acquisition. Program PICPIO acquires an image using two LeCroy 3512 ADCs that are located in the minicrate of the LeCroy 3500. The signals produced by the Picker Dynamo Camera that describe the X,Y coordinates of a scintillation are in the range of 0- to 2-Vdc. As it happens, the LeCroy 3512s can produce seven bit digitization wherein the full scale is 2.1 Vdc. Thus, a gain adjustment computation for the values of the X,Y coordinates is not required, and a 14-bit pixel address can be computed by merely concatenating the 7-bit X and Y values to form a 14-bit pixel address. PICPIO continues to collect data until stopped. It is possible to stop PICPIO and restart it to continue the acquisition of a particular image; or acquisition of a new image can be started, as specified by the operator.

Image Centering. The LeCroy 3512s have zero offset adjustments that must be finely tuned to produce an image that is centered in its frame of reference. Part of the decoding process requires an accurately centered image to preserve geometric relationships between source and camera. Program CENTER will perform the centering of an image that was acquired using misadjusted zero offsets. The use of this program permits very coarse adjustments of the 3512 zero offsets.

Image Interpolation. Proper application of Eq. (10) requires an appropriate magnification of the encoded image to perform the decoding of an object that is located at a distance from the coded aperture. Proper magnification of a planar image parallel to the detector face involves extracting only that portion of the encoded image that covers the same area of the detector as a shadow of exactly one period of the aperture pattern that would be cast by a single-point source that is located in the same plane as the object being imaged. In addition to the proper scaling of the encoded image, it is also necessary to sample the encoded image with an integer number of samples per pinhole area (Fenimore and Cannon[5]). Since it is unlikely that the detector will naturally provide samples at the needed spacing, it is necessary in practice to perform an interpolation on points nearby the desired location in order to obtain a proper value. Program PINTERP performs an interpolation upon the raw encoded image acquired by PICPIO and centered by CENTER to obtain a encoded image that represents a planar source that is a specified distance from the aperture.

Image Decoding. Program HATST implements the solution of Eq. (10) using Hadamard transform techniques. The aperture pattern consists of a 33-by-31 array of elements. Fenimore and Weston[2] have shown that a encoded image can be fine sampled, and that if delta decoding is used on each fine sample, Eq. (10) can be solved for cases where the length of the sequence with fine samples is $n_f(2^m - 1)$ where n_f is a positive integer. The introduction of fine sampling into the computation merely increases the number of computations to be performed by a factor of n_f over the case of a sequence of $2^m - 1$. To increase the resolution, this fine sampling is done where $n_f = 9$. Thus, the image to be decoded has 99 columns and 93 rows. Approximately 30 s are required to decode this image.

Image Display. The LeCroy 3500 possesses only marginal grey-scale display capabilities. Nevertheless, a software package, IMPLT, will display monochrome images in any stage of processing using 7 levels of grey. This display program will allow the user to do image enhancement by permitting the user to specify which pixel values represent black and white.

Other Image Processing. Certain other image processing software packages have been written to perform useful functions not listed above. With these packages, an image can be rotated, scaled, and the pixel value clipped. It is also possible to compute the sum image of two images and the difference image of two images. A difference image computation can be used to remove a background from an image.

4. Source Studies

A source of 1.5 mCi of ^{57}Co was placed at a distance of 27 m from the URA, which was 20 cm from the detector crystal. Figure 3a shows the encoded image of this source, whereas Fig. 3b shows the decoded image of this object. This is almost a perfect decoding.

A distributed source behind heavy shielding was also imaged (Fig. 4). This source was a 220-g plate (5 by 17 by 0.6 cm) of bulk plutonium (11.8% ^{240}Pu). The shielding used was 0.3 cm of lead, 2.5 cm of steel, and 10 cm of a dense plastic material. Figure 4a shows the encoded image of the distributed source, and Fig. 4b shows the decoded image. The image was acquired using the 414-keV spectral line.

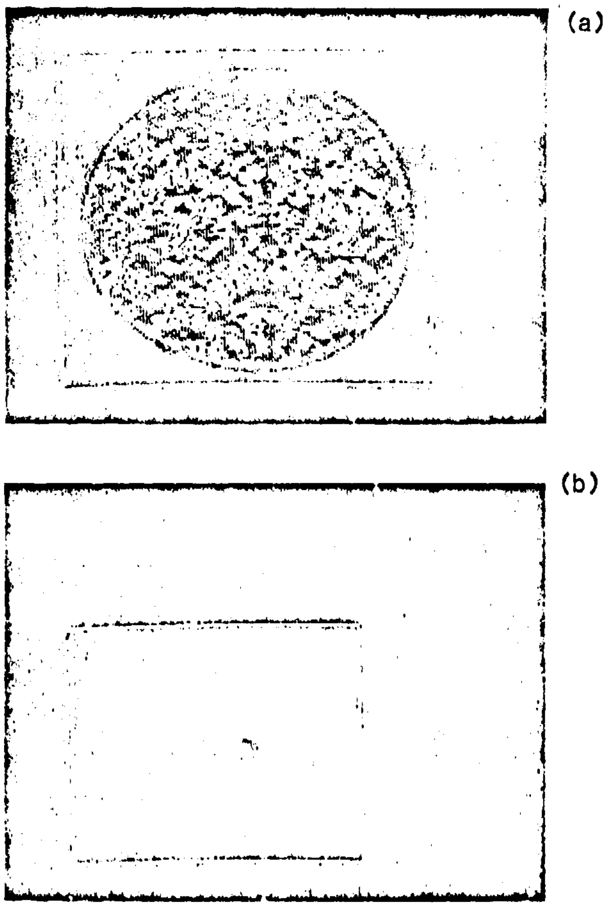

Fig. 3.
^{57}Co at 27 m from aperture. (a) Encoded image. (b) Decoded image.

The URA in Fig. 4 was 77.5 cm from the plutonium plate and 20 cm from the detector crystal. From the decoded image we determined that one piece of plutonium was present whose dimensions, 15.5 by 7.7 cm, agree well with the known dimensions. Such information supplements information acquired from more conventional measurement techniques, such as gamma-ray spectroscopy and neutron counting. Thus, the imaging method enhances our confidence in verifying the contents of a sealed container.

5. Conclusion

The Anger camera represents the first time the fast delta Hadamard transform analysis has been used in an imaging system. This instrument permits the examination of large, sealed packages that may contain radioactive sources that emit gamma rays. Such an examination provides information describing the location of the source and can be done without opening the package even, as Fig. 4 reveals, in the presence of heavy shielding.

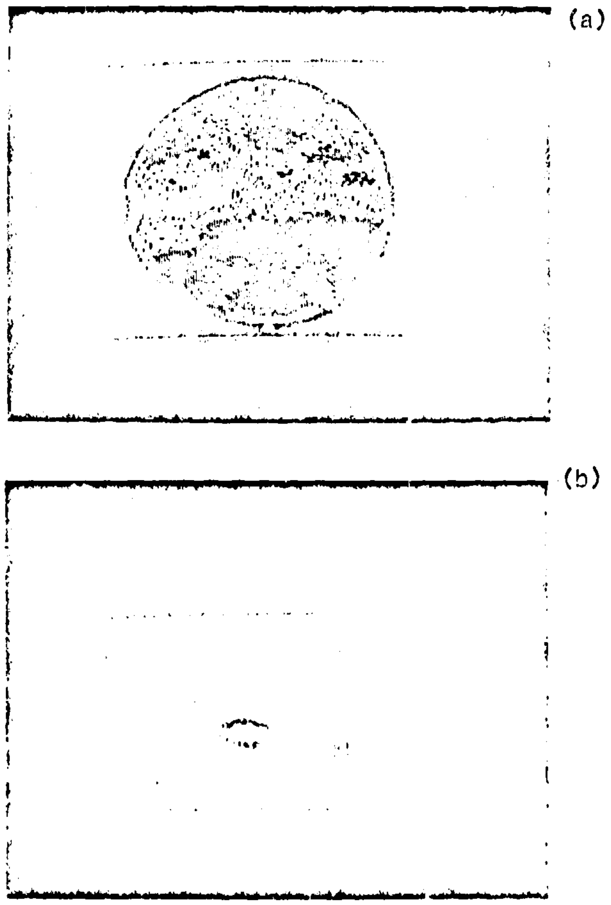

Fig. 4.
Plutonium plate with heavy shielding. (a) Encoded image. (b) Decoded image.

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