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GAMMA-RAY DATA INTO A SINGLE ASSAY VALUE**

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A TECHNIQUE FOR COMBINING NEUTRON AND GAMMA-RAY DATA INTO A SINGLE ASSAY VALUE*

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Abstract

We have explored the potentials of using both neutron and gamma-ray measurements on a single item and combining these data into a single assay value. The purpose was to improve assay capability for sample matrices that are difficult to measure. We chose an empirical approach because we wanted to address difficult-to-measure items for which the assay problem is complex. We used the tomographic gamma scanner; a passive, high-efficiency neutron counter with add-a-source and multiplicity; and an active neutron, californium shuffler to obtain measurements. Twenty-four 200-L drums were measured with various matrices using all three machines. The matrices were chosen specifically to span the difficult-to-measure assay problems for some or all of the instruments. For example, we measured a drum filled with concrete and another filled with metal. The data from these measurements were analyzed using the alternating conditional expectation algorithm, which is one of a class of generalized additive models.[1-3] Other data fusion algorithms are also possible and are being explored. The intent was to find ways to combine the data that would reduce the matrix-induced measurement error.

INTRODUCTION AND PREVIOUS WORK

Because neutron and gamma-ray measurements have complementary strengths and weaknesses, a combination of these methods should significantly improve the overall assay accuracy. Moreover, improved assay capability is necessary to extend the capabilities of waste assay instruments so that they can also satisfy requirements for safeguards accountability and safeguards termination. We have already successfully applied this principle by combining essentially disparate information from neutron flux monitors in the californium shuffler using the alternating conditional expectation (ACE) algorithm.[1-5]

We have extended this concept to the broader problem of combining neutron and gamma-ray information. The intent is to combine neutron and gamma-ray data to obtain a single assay value that is more accurate and more robust than either method alone. To give this approach the best chance for success, we started with the most effective nondestructive assay instruments available. For gamma-ray measurements, we used the tomographic gamma scanner (TGS).[6] For neutron measurements, we used the high-efficiency, passive-neutron, multiplicity counter with add-a-source (AAS).[7] For active neutron measurements, we used the californium shuffler.[8]

THE ALTERNATING CONDITIONAL EXPECTATION ALGORITHM

The ACE technique is a computer algorithm that can perform a multivariate regression on data without having a functional form and starting parameters in advance.[1-3] The basis of the technique is to develop a series of transformations on each of the regression variables, Y and X_i :

$$\begin{aligned}
Y' &= \Theta(Y) , \\
X_1' &= \Phi_1(X_1) , \\
X_2' &= \Phi_2(X_2) , \\
&\vdots \\
X_n' &= \Phi_n(X_n)
\end{aligned} \tag{1}$$

These transformations are subject to the boundary condition that

$$Y' = X_1' + X_2' + X_3' + \dots X_n' . \tag{2}$$

Equation 2 can be treated as a constraint; the transformations are developed subject to this condition. Once the ACE algorithm has obtained the specific data transformations, the compensation function can be constructed by substituting the transformations (Eq. 1) into Eq. 2 and algebraically inverting them as follows:

$$Y = \theta^{-1} \left[\sum_i \phi_i(X_i) \right] . \tag{3}$$

The mechanics of the ACE technique are somewhat more involved. The algorithm is numerical, so the results must be converted to an analytic form. The ACE software generates a set of paired points, $\{Y, X_1, X_2, \dots X_n\}_i$, for each independent and dependent variable. The set spans the entire data set. To convert the set of raw data versus transformed data points to analytic functions, we used a commercial bivariate fitting program called TableCurve.TM Each ACE transform was fitted using conventional regression to a simple function. These functions were then algebraically combined in Eq. 3 and the equation was solved for the dependent variable.

A final step was performed on the analysis to ensure that the optimum fit had been obtained. Another commercial package was used to perform a conventional nonlinear least-squares regression of the function on the data set. Because this program uses conventional methods, a functional form and initial values for the parameters were required. However, these were provided by the ACE analysis. The conventional multivariate regression improved the final results only slightly.

EXPERIMENTAL APPARATUS AND DATA

The first step in this program was the development of an instrument that could be used for a source of data. We already had available in at Los Alamos a TGS, which could be used for gamma-ray measurements. However, a neutron instrument was also needed. Moreover, we wished to have both passive and active neutron measurements. Therefore, we designed and built the hot-cell, combined shuffler and passive AAS instrument. This system can operate as both a californium shuffler and as passive neutron counter with AAS. Both modes were used for this project. This machine was built into the hot cell to make use of the shield walls already available. It was produced at modest cost and is now also used for waste assay training.

In order to keep costs modest, the entire system was built into the NIS-5 hot cell. The hot cell provides extensive shielding without additional cost. Both the add-a-source and the shuffler californium sources are

kept inside the hot-cell walls. The hot cell itself provides much of the instrument mechanical support. The result was that a full 55-gal. drum shuffler and combined AAS instrument could be built for a modest cost. Figure 1 is a picture of the hot-cell AAS (HCAS) system.

The next phase of this project was the measurement of a sample set that spanned the matrix types defined in the measurement program. The samples were chosen so that the most difficult and challenging matrix interferences could be tested and evaluated. For example, we tried matrices made of metals that are highly shielding to gamma rays. We also tried matrices composed of polyethylene for the high hydrogen concentration. Hydrogen is the most effective moderator of neutrons. To exacerbate this effect, matrices were constructed that had both neutron moderation (hydrogen in the form of polyethylene) and neutron absorbers (boron). To make the problem even more difficult, matrices were tried that combined the most difficult aspects for both neutron and gamma-ray systems. Table I, below, lists the type of matrices that were measured.

TABLE I: Drum standards used for these experiments.	
1	Empty
2	Polyethylene Shavings, 10.5 kg
3	Polyethylene Beads, 60 kg
4	Wood
5	Polyethylene Tubes, 33 kg
6	Polyethylene & Vermiculite, in ratio: 50/16
7	Aluminum and Polyethylene Layers
8	Aluminum and Paper
9	Mixed Metals
10	Graphite Blocks
11	Concrete Rubble
12	Sand
13	Paper
14	Inhomogeneous Mixture of Materials
15	Polyethylene and Water
16	Polyethylene & Borax
17	Portland Cement
18	1/2 Portland Cement, 1/2 empty
19	Cement & Tungsten
20	Metal & Polyethylene Beads
21	1/2 Drum Sand & Polyethylene
22	Glass Beads & Tungsten
23	Rashig Rings

For each matrix type, three assays were run: the TGS, the passive neutron counter using the AAS matrix correction, and the shuffler active neutron assay. The last two assays were performed on the same machine, the hot cell AAS counter that was designed and built as part of this experiment. In addition, each assay was performed at two locations, at the center of the drum and at one of the tubes at one half the drum radius. All sources were located at the vertical midplane of the drum. These measurements comprised the data set that were used for the empirical data analysis.

Fig. 1. Picture of the new 55-gal. drum-sized, hot-cell, combined shuffler and AAS.

Several different types of data were obtained for each assay. The different types of data extend the data combination possibilities, so long as each is mostly linearly independent from the others.

ACE DATA ANALYSIS

The initial problem in the data analysis was to consider some kind of functional form that could combine the data in a logical fashion. Since there are at least two (neutron and gamma) independent assay methods, each will have an error relative to the known value. Which one should we select to correct? Is one better than the other under certain circumstances, and can we determine those conditions from the data alone? Because the focus was on correcting matrix and heterogeneity problems, we used many different matrix types but only a single mass value, therefore the trivial approach of attempting to construct a function: $\text{mass} = f(\text{TGS assay, neutron assay})$, was not possible. We decided to use the TGS data to correct the neutron assay, use the neutron data to correct the TGS assay, and then combine these two corrected values in a weighted average. We used the ACE algorithm to construct the two correction functions. For example, to correct the TGS assay we constructed a correction function, CF , that was a function of the neutron data:

$$\frac{\text{TGS_true}}{\text{TGS_assay}} = CF = f(\text{all neutron parameters}) \quad (4)$$

The ACE algorithm was used to construct this multivariate function, f , that was a function of any selected neutron parameters. This process was then repeated for the neutron correction factor, using all of the TGS gamma-ray measurement parameters. The results were the corrected TGS and AAS assay values.

To illustrate this process, Fig. 2 is a plot of the ACE transforms obtained to correct the TGS assay using neutron data. After searching through many different data combinations, we found that the best correction function was obtained using the ratio of the TGS to multiplicity assay value and the AAS correction factor. ACE constructed a multivariate function of these parameters.

Fig. 2. Plots of the transforms developed by ACE for the TGS correction function.

To construct the actual function, the numerical transforms in Fig. 2 are fitted to bivariate curves. Figures 3 and 4 are examples of the curves obtained for this data set. The functions for these curves are then algebraically combined into the correction factor function, CF , for the TGS assay. The result was

$$CF = \exp \left[K_1 + K_2 \cdot \sqrt{AAS_COR} + K_3 \cdot \left(\ln \left(TGS / Mult \right) \right)^2 + K_4 \cdot \ln \left(TGS / Mult \right) \right] , \quad (5)$$

where K_i are constants, AAS_COR is the AAS correction factor, and $TGS/Mult$ is the ratio of the TGS assay to the multiplicity assay values.

TGS Assay to True
 $y = a + b(\ln x)$

Fig. 3. Bivariate curve fit of the correction factor dependent variable for the TGS correction function.

TGS to Multiplicity
 $y = a + b(\ln x)^2 + c \ln x$

Fig. 4. Bivariate curve fit of the ACE transform for the TGS to multiplicity assay ratio. This is used for the TGS correction function.

Using this correction factor, the assay accuracy for the TGS was improved from 7.53% to 5.1%. These results are shown in Fig. 5.

Comparison of Corrected TGS vs Raw TGS

Fig. 5. TGS assay errors for each of the data points. Both the uncorrected and corrected TGS results are shown.

A similar process was followed for the correction of the AAS data. The ACE transform indicated that the correction factor function depended on the TGS ratio of net counts to assay value (effectively the TGS attenuation correction) and the ratio of the TGS to AAS assay values. The correction function is

$$CF = \left[\frac{K_1 + K_2 \cdot \ln(CFAT) + K_3 \cdot (\ln(CFAT))^2 + K_4 \cdot (\ln(CFAT))^3}{K_5 \cdot \ln(TGS_AAS) + K_6 \cdot (\ln(TGS_AAS))^2} + K_7 \right]^{K_7}, \quad (6)$$

where CF is the correction function, $CFAT$ is the ratio of TGS counts to TGS assay value, TGS_AAS is the ratio of the TGS to AAS assay values, and the K_i are constants. Figure 6 plots the improvement in the AAS assay accuracy.

Comparsion of Corrected Add-a-Source Data vs. Raw Data

Fig. 6. AAS assay errors for each of the data points. Both the uncorrected and corrected TGS results are shown.

In both cases the functional form developed by the ACE analysis was optimized using standard least-squares regression. ACE provided the regression function and initial parameter values. These were optimized using regression fitting. Figure 7 shows the regression output for the AAS data and how closely the function form of the AAS correction meets the optimal value.

Once the corrected values for the AAS and TGS assays were obtained, these two assays were combined into a single assay value. We chose a model of the form

$$\text{True_Assay} = f \times \text{TGS_Assay} + (1 - f) \times \text{AAS_Assay}.$$

The parameter, f , was selected to obtain the most accurate assay value for each data point. The final step was one more application of ACE to construction a function, F , that closely produced the proper f values. This function could depend on any of the measurement values, both neutron and gamma. The application of the ACE process followed identically the earlier two examples. Figure 8 plots the final results. The combined and corrected assay data are compared with the original, uncorrected AAS and TGS values. The improvement is significant, the original TGS error was 7.53%, the original AAS error was 14.1%, and the corrected and combined error was reduced to 3.3%.

AAS Correction vs. Scientist's Calculated Correction

Fig. 7. The calculated correction factor plotted against the ideal correction value for the AAS correction data.

Comparison of Combined Assay vs. Raw AAS and TGS

Fig. 8. Comparison of errors for the combined, corrected assay results, and the original TGS and AAS assays for the entire data set.

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