REDUCTION OF BACKGROUND BY HIGHER ORDER STATISTICS WITH NMIS

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ABSTRACT

Measurements that accumulate the rate of real coincidence between multiplets of detection events (groupings of arbitrary order, e.g., one event, two events, three events, etc.) can yield spurious results if background events arise from processes (e.g., spontaneous fission or neutron spallation) that themselves produce correlated multiplets. This is particularly true if this background varies significantly over time or from one location to another, as it often does in operating facilities, i.e., those not specifically designed to support *experimental* radiation measurements but that instead rely upon the support of precise radiation measurements for, e.g., NMC&A. In particular, both the quantity and location of radioactive material in weapons facilities changes frequently and unpredictably, and so the background due to the presence (or absence) of this material is completely out of the control of the radiation measurement analyst. Furthermore, numerous Nuclear Materials Identification System (NMIS) measurements have revealed that background often contains mutually correlated events even in the complete absence of material (e.g., ^{240}Pu) with a significant spontaneous fission rate. The technique subsequently described removes the effects of such *self-correlated* background from active NMIS measurements. It could be adapted to other active radiation measurements.

INTRODUCTION

Standard statistics accumulated by NMIS include the distribution of two-way coincidence between all pairs of channels over the time-delay between channels

$$C_{xy}(\tau_{xy}) \;=\; \overline{x(t_x)\,y(t_y)}\,\Big|\,\tau_{xy} = t_y - t_x \quad ,$$

where $x(t_x)$ and $y(t_y)$ respectively represent the stream of events in channels x and y as a function of independent times t_x and t_y. Consequently $C_{xy}(\tau_{xy})$ yields the *total* coincidence rate between channels x and y when they are delayed relative to one another by $\tau_{xy} = t_y - t_x$. The rate of *real* coincidence between the two channels is just

$$R_{xy}(\tau_{xy}) \;=\; C_{xy}(\tau_{xy}) \;-\; \bar{x}\,\bar{y} \quad ,$$

where $\bar{x}$ and $\bar{y}$ respectively denote the mean total count rate in channels x and y, such that their product $\bar{x}\,\bar{y}$ yields the rate of *accidental* coincidence between the two channels. The distribution of real two-way coincidence is often called the covariance between channels or the *second-order cumulant*.

When channel x is acquired from an active source and channel y is acquired from a radiation detector, $R_{xy}(\tau_{xy})$ yields the distribution of source-correlated detector counts over the time-delay τ_{xy} between the occurrence of the detector count and the initiating source emission. This statistic is analogous to the distribution accumulated by a pulsed neutron measurement. Note in particular that because background events are statistically independent of source emissions, this distribution is independent of background. Furthermore, the area under this distribution is the mean *source-correlated* detector count rate, i.e.,

$$\int d\tau_{xy}\; R_{xy}(\tau_{xy}) \;=\; \overline{y\,|\,x} \quad .$$

When both channels x and y are acquired from unique radiation detectors, $R_{xy}(\tau_{xy})$ yields the distribution of mutually correlated detector count pairs over the time-delay τ_{xy} between the first and second count in the correlated pair. This statistic is analogous to the distribution accumulated by a two-detector Rossi-α measurement.[a] Recognize that if no two-way pairings of background events are mutually correlated, then this distribution will also be independent of background. However, if background arises from processes (e.g., spontaneous fission or neutron spallation) that produce correlated *multiplets*, then these processes, though statistically independent of active source emissions, will nevertheless contribute to this second-order cumulant between detectors.

Such self-correlated background *has been observed in numerous measurements, even in the complete absence of any material (e.g., ^{240}Pu) with a significant spontaneous fission rate.* This observation is relevant not only to NMIS measurements but also to *any* measurement technique that acquires statistics yielding the rate of correlated multiplet detection. These techniques include single- and two-detector Rossi-α, Feynman variance, and multiplicity measurements.

Subsequently, a method is described to remove the contribution of self-correlated background from the second-order cumulant between detectors to produce a distribution that is completely independent of background. A variant of this method could be implemented to remove the contribution of self-correlated background to other active measurements.

METHOD

NMIS is also capable of accumulating higher order statistics.[1] In particular, NMIS accumulates the distribution of three-way coincidence between all triplets of channels:

$$C_{xyz}(\tau_{xy}, \tau_{xz}) \quad = \quad \overline{x(t_x)\, y(t_y)\, z(t_z)}\,\Bigg|_{\substack{\tau_{xy} = t_y - t_x \\ \tau_{xz} = t_z - t_x}} \quad .$$

Recognize that $C_{xyz}(\tau_{xy}, \tau_{xz})$ yields the distribution of the *total* coincidence rate between channels x, y, and z when channel y is delayed relative to x by $\tau_{xy} = t_y - t_x$ and channel z is delayed relative to x by $\tau_{xz} = t_z - t_x$. The *real* three-way coincidence rate between channels is

$$R_{xyz}(\tau_{xy}, \tau_{xz}) \quad = \quad C_{xyz}(\tau_{xy}, \tau_{xz}) \quad - \quad \overline{x}\, R_{yz}(\tau_{xz} - \tau_{xy}) \quad - \quad \overline{y}\, R_{xz}(\tau_{xz}) \quad - \quad \overline{z}\, R_{xy}(\tau_{xy}) \quad - \quad \overline{x}\,\overline{y}\,\overline{z} \quad ,$$

where the last four terms yield the rate of *accidental* three-way coincidence. Specifically, the last term is the rate of accidental three-way coincidence due to triplets of events that are all mutually uncorrelated, and the preceding three terms yield the rate of accidental coincidence when a correlated pair of events is uncorrelated to the third event in the triplet. The distribution $R_{xyz}(\tau_{xy}, \tau_{xz})$ of real three-way coincidence between channels is sometimes called the bicovariance or, preferably, the *third-order cumulant*.

Recognize that if channel x is acquired from the source and channels y and z are acquired from detectors, $R_{xyz}(\tau_{xy}, \tau_{xz})$ yields the distribution of mutually correlated detector count pairs that are in turn correlated to a source emission. Note in particular that this distribution is independent of background, even self-correlated background, because background is statistically independent of source emissions.

Furthermore, observe that

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[a] Note also that if the two channels are not unique, this statistic is analogous to the distribution accumulated by a single-detector Rossi-α measurement.

$$\int d\tau_{xy}\ R_{xyz}(\tau_{xy}, \tau_{xy} + \tau_{yz}) \quad = \quad \int d\tau_{xz}\ R_{xyz}(\tau_{xz} - \tau_{yz}, \tau_{xz}) \quad = \quad R_{yz|x}(\tau_{yz})$$

yields the portion of the second-order cumulant between detectors that arises strictly due to source-correlated events. The remainder is the contribution of self-correlated background, i.e.,

$$R_{yz}(\tau_{yz}) \quad = \quad R_{yz|x}(\tau_{yz}) \quad + \quad R_{yz|\tilde{x}}(\tau_{yz}) \quad ,$$

where $R_{yz|\tilde{x}}$ is the contribution that is *not* correlated with the source; if the object measured does not contain materials with an appreciable spontaneous fission rate, then this contribution arises from self-correlated background.

Consequently, this method allows the *total* second-order cumulant between detectors to be "split" into *two* components: one that arises from source-correlated events, and the other that arises from self-correlated background. The only requirement to implement this technique is that the active source must produce a signal that can be acquired to detect the time of source emissions; candidate sources include the ^{252}Cf ionization chamber and associated-particle neutron generators. A variant of this technique has also been implemented in NMIS to remove the contribution of self-correlated background from multiplicity measurements.[2]

RESULTS

To illustrate the efficacy of this method, a test measurement was performed using a ^{252}Cf ionization chamber as the active source and an array of fast plastic scintillators to detect neutrons and gammas. The source and detectors were separated by approximately one meter with no material between them; however, roughly two meters away was a large mass of fissile material containing no plutonium. Three measurements were performed in this configuration as illustrated in Fig. 1. In each measurement the distance between the ionization chamber and the detector array was maintained constant while the orientation of the chamber and detectors relative to the external mass of fissile material was changed. Note that from the first to the third measurement, the distance between the detectors and the external fissile material increased.

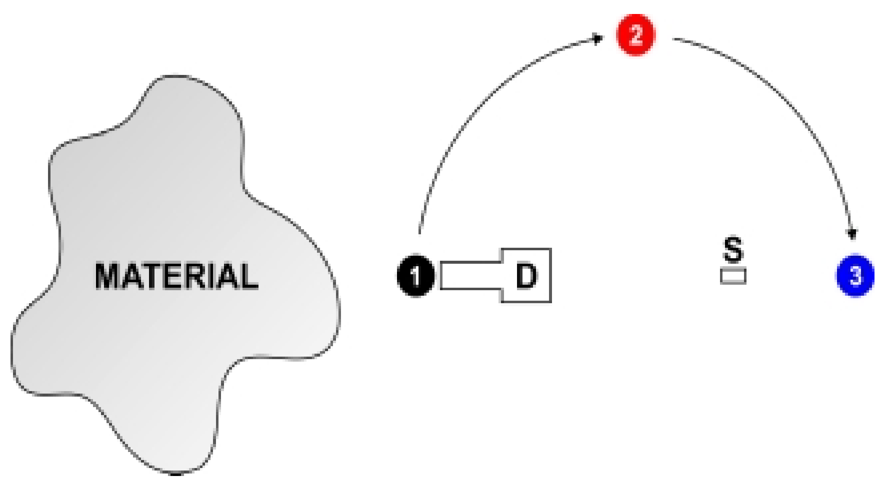

Figure 1. Three test measurements performed using a ^{252}Cf ionization chamber as the active source and an array of fast plastic scintillators to detect neutrons and gammas. The distance between the source (S) and the detectors (D) (approximately 1 m) was maintained constant while the orientation of the source and detectors relative to a mass of external fissile material was changed.

Now examine Fig. 2, where the distribution of mutually correlated detector count pairs is shown for each of the three test measurements. Observe in particular that the rate of real coincidence between detectors increased significantly as the distance between the detectors and the external fissile material decreased. This occurred even though *the external material contains no plutonium*, and it introduced an undesirably large uncertainty (5.4%) in the peak rate of real coincidence between detectors. This large uncertainty, which arose solely from self-correlated background emanating from the fissile material, can decrease the reliability of identification via pattern recognition methods when a weapons component is placed between the source and detectors.

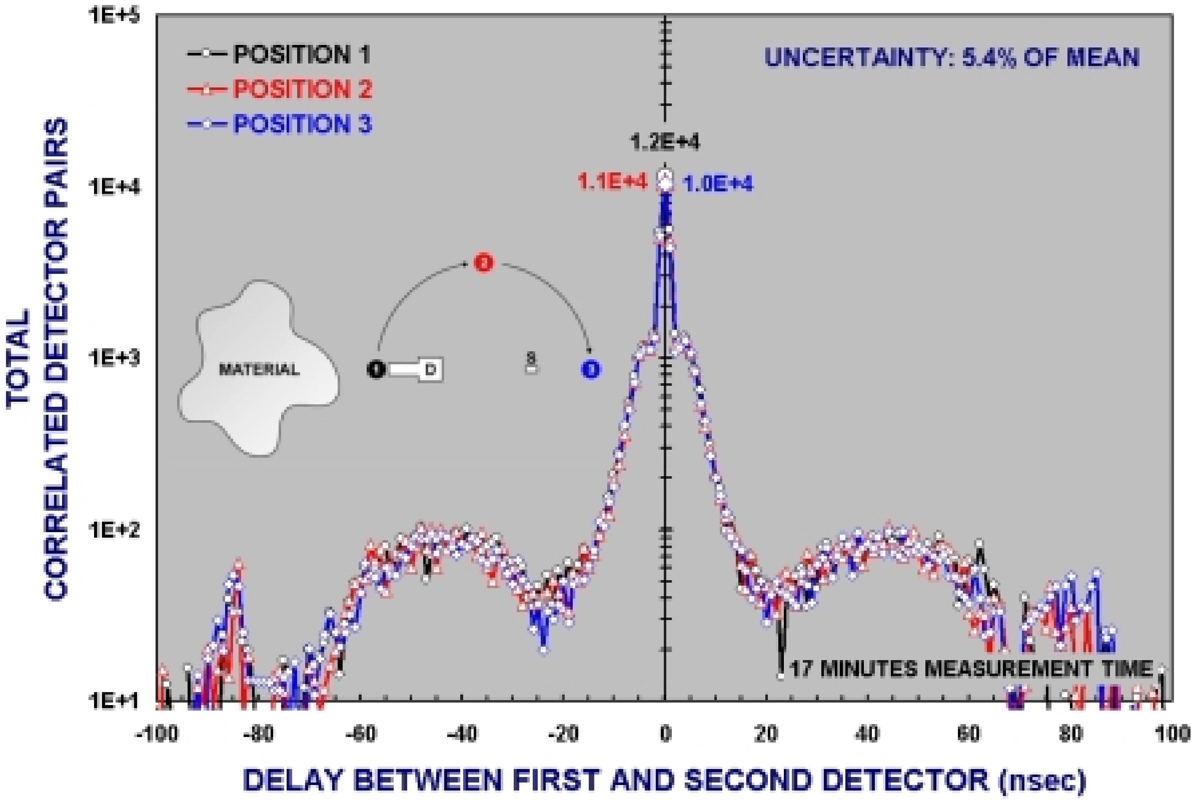

Figure 2. Distribution of mutually correlated detection events measured for each orientation of the source and detectors relative to the external mass of fissile material. The source of the observed variability is self-correlated background emanating from the external fissile material.

The potential processes producing self-correlated background in the absence of plutonium include:

- Spontaneous ^{252}Cf fission events that are not counted by the ionization chamber. However, the design of the ionization chamber has been optimized such that typically greater than 90% of all spontaneous fission events are counted; unregistered fission events cannot account for the variation observed in the rate of correlated detector pairs. Furthermore, because the distance between the source and detectors is maintained constant, this source of self-correlated background did not change as a function of distance from the external fissile material.

- Neutron-scattering between detectors. Because the detectors are in close proximity to each other, sometimes a single neutron can induce a count in one detector and still have enough energy to induce a subsequent count in another detector. However, the discriminators were set with a lower threshold of roughly 1 MeV; consequently, the incident energy of a single neutron must typically be greater than 2 MeV to induce two counts in separate detectors.[b] This process alone cannot account for the variability observed in the coincidence rate between detectors.
- Spontaneous fission of ^{238}U. However, the mass of fissile material present was not sufficient to cause the large variation observed in the rate of coincidence between detectors.
- Neutron spallation off uranium by cosmic radiation. This is difficult to quantify; however, it seems extremely unlikely that this process could have produced a sufficient number of correlated neutrons to introduce the variations observed.
- Beta decay de-excitation gamma emissions by daughter products of uranium alpha decay. This seems to be the most likely culprit because nuclides produced by alpha decay of uranium frequently beta decay and subsequently release a cascade of de-excitation gammas in rapid succession.

This last process, which produces numerous correlated gammas, is the most likely source of the self-correlated background emanating from the external fissile material. The greatest variability in the rate of coincidence between detectors was observed to occur due to coincident gammas.

Examine Fig. 3, which shows the distribution of mutually correlated detector count pairs that are in turn correlated to a source emission. As indicated in Fig. 3b, Three classes of two-way correlated detector counts contribute to this distribution.

- Gamma-gamma pairs: because all gammas travel at the same speed, coincidence between two gammas occurs at short delays between detectors. Furthermore, because the speed of light far exceeds the typical speed of neutrons, compared to pairs that involve one or more neutrons, these gamma-gamma pairs are detected shortly after the initial event that produced them. Hence this class of correlated detector counts appears as a narrow peak in the distribution near the origin.
- Gamma-neutron pairs: when a gamma and a neutron are produced by the same event, the gamma is always detected first. The delay between the initial event and the gamma detection is short and essentially constant, whereas the delay between the initial event and the neutron detection tends to be much longer and is distributed according to the neutron spectrum. Hence, this class of correlated detector counts appears as two narrow ridges in the distribution oriented along the principal axes.
- Neutron-neutron pairs: because the delay between the initial event and each neutron detection is distributed according to the neutron spectrum, this class of correlated detector counts appears as a broad peak in the distribution centered at relatively long delays and oriented along the diagonal. In the complete absence of neutron scattering between detectors, this feature of the distribution is unimodal. The two diagonally oriented “side lobes” evident in this feature of the distribution arise due to neutron scattering between detectors. They were not observed to vary significantly.

The projection of this distribution along the diagonal, shown in Fig. 3c, illustrates the shape of the portion of the distribution of real coincidence between detectors that arises strictly due to source-correlated events. The remaining distribution of coincident detector counts arises from *self-correlated background* emanating from the external fissile material, and as shown in Fig. 4, it is the source of the variability observed in coincidence rate between detectors.

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[b] Recall that plastic scintillators principally detect neutrons scattering off hydrogen nuclei in the detector crystal. The energy lost during a single scattering event varies between zero and the entire incident energy, and on average the energy lost is one-half the incident energy. Consequently, on average a neutron must have an incident energy greater than twice the discrimination threshold to induce two counts in separate detectors.

In contrast, the distribution of real coincidence between detectors that arises solely due to *source-correlated events* does not vary significantly with proximity to the external fissile as illustrated in Fig. 5. Numerous tests have subsequently shown that this quantity is a more robust means to identify weapons components using pattern-recognition methods. Consequently, acquisition of this distribution is now standard in all active NMIS inspection measurements.

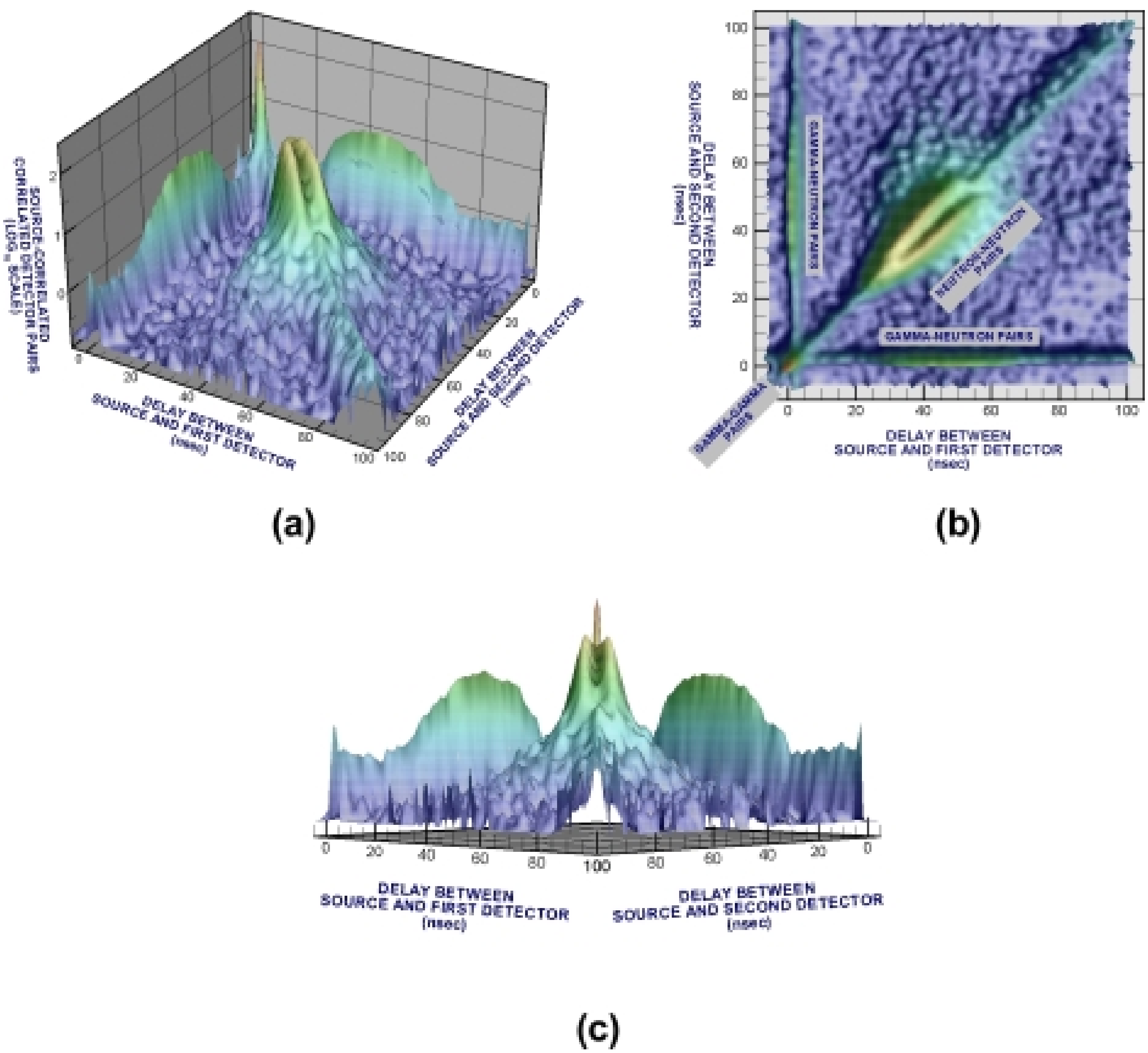

Figure 3. Distribution of mutually correlated detector count pairs that are in turn correlated to a source emission (a). Three classes of correlated detector pairs contribute to the distribution (b). The diagonal projection of the distribution illustrates the shape of the distribution of mutually correlated detector pairs arising solely from source emissions (c).

CONCLUSIONS

Background radiation in weapons facilities due to the presence (or absence) of radioactive material is completely out of the control of the radiation measurement analyst because the quantity and location of radioactive material changes frequently and unpredictably. In particular, background can yield spurious results if background events arise from processes (e.g., spontaneous fission or neutron spallation) that themselves produce mutually correlated detection events. Numerous NMIS measurements have revealed that background often contains mutually correlated events even in the complete absence of material (e.g., ^{240}Pu) with a significant spontaneous fission rate.

The preceding technique removes the effects of such *self-correlated* background from active NMIS measurements. It's implementation has consequently enhanced the robustness of active NMIS inspection measurements performed to identify weapons components. It could be adapted to other active radiation measurements.

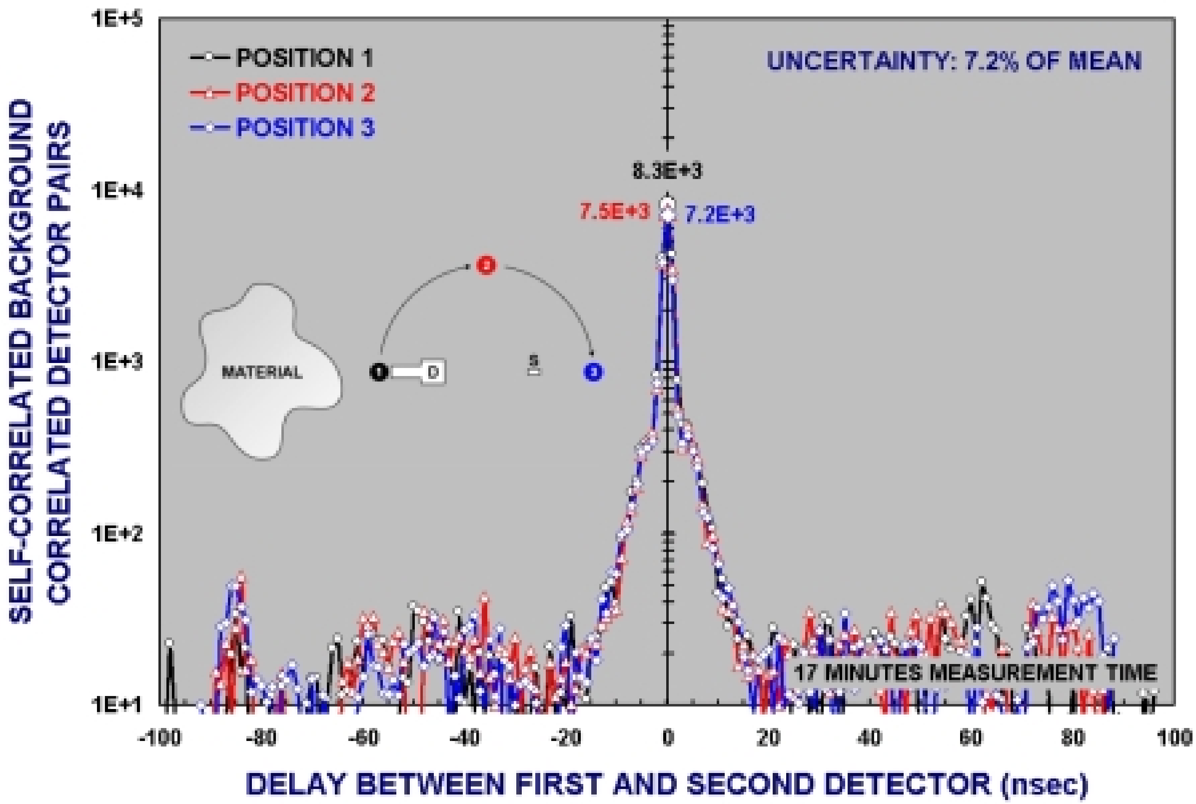

Figure 4. Distribution of mutually correlated detection events arising from self-correlated background measured for each orientation of the source and detectors relative to the external mass of fissile material. The source of the observed variability is the self-correlated background emanating from the external fissile material.

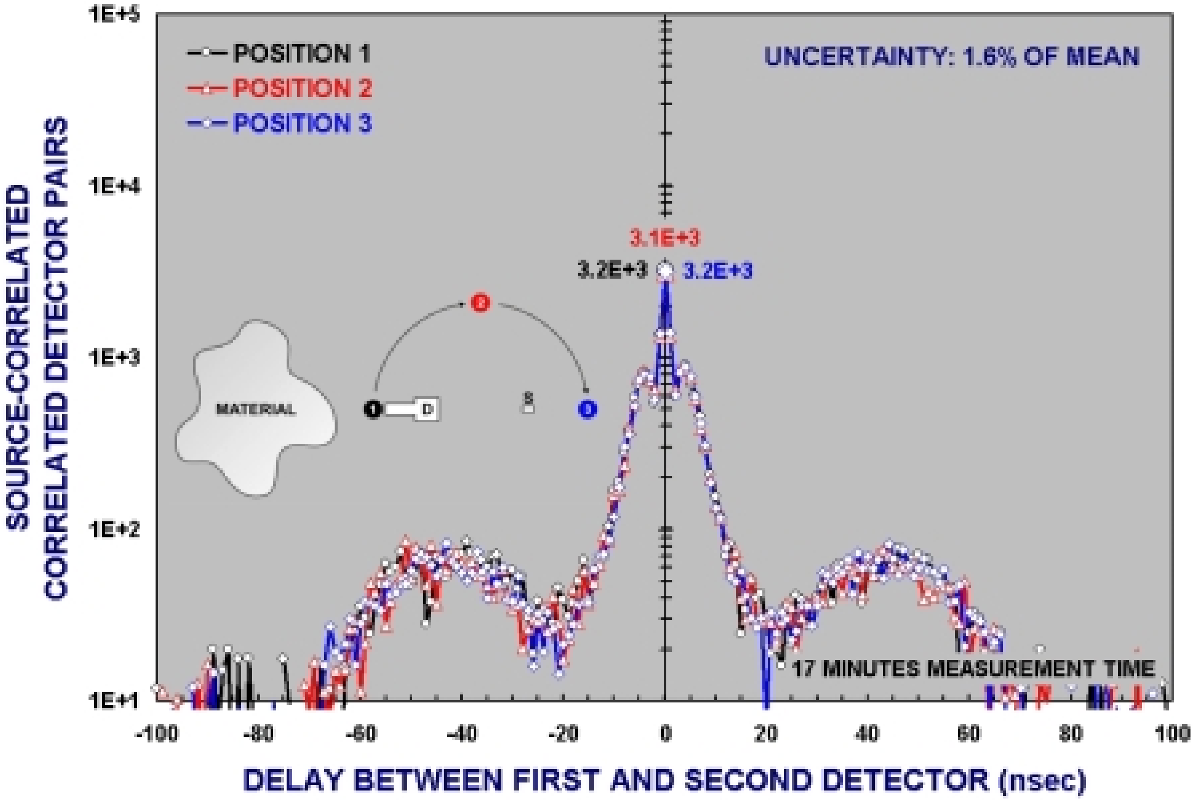

Figure 5. Distribution of mutually correlated detection events arising solely from the active source measured for each orientation of the source and detectors relative to the external mass of fissile material. This distribution is independent of all background, including self-correlated backgroud. Consequently it does not vary significantly with proximity to external fissile material.

REFERENCES

1. J. K. Mattingly, “High Order Statistical Signatures from Source-Driven Measurements of Subcritical Fissile Systems”, Y/LB-15,966/R1, Oak Ridge Y-12 Plant, 1998.
2. J. A. Mullens, J. K. Mattingly, T. E. Valentine, J. T. Mihalczo, and R. B. Perez, “Incorporation of Neutron and Gamma Multiplicity Measurements in the ORNL Nuclear Materials Identification System (NMIS): Passive and Active Measurements,” Y/LB-15,984/R2, Oak Ridge Y-12 Plant, 1998.