# SIMULATION OF HIGHER ORDER STATISTICS MEASUREMENTS USING MCNP-POLIMI

Sara A. Pozzi and John T. Mihalczo
Oak Ridge National Laboratory
P.O. Box 2008, MS-6010, Oak Ridge, TN 37831-6010

## ABSTRACT

A post-processing code has been developed to simulate third-order time-correlation measurements with MCNP-PoliMi. The three-way coincidence distribution is measured using three detectors: typically three liquid or plastic scintillators, or a timed source and two liquid or plastic scintillators. In the experiments considered here, the scintillators are sensitive to fast neutrons and gamma rays, and the correlations are performed with nanosecond resolution. The code allows the user to split the total signature into its components. One split is performed according to the particle types that were detected, and another is performed according to the generation number of the particles detected.

## INTRODUCTION

MCNP-PoliMi [1] is a modified version of the MCNP-4C code that provides an improved representation of the physics of the processes involved in correlation measurements on fissile materials. The standard MCNP code was not designed for the simulation of second or third-order signatures from the signals of detectors. Indeed, the simulation of higher order signatures cannot be based on average values, and average values are used in the standard MCNP code in the production of neutrons from fission and secondary gamma rays [2].

Previous studies have shown the benefits of conducting time-correlation measurements of the signals from three detectors [3]. This paper illustrates the capabilities of a specifically designed post-processing code, for use on the MCNP-PoliMi data output. The code includes a basic model of the detection process in scintillation detectors [4], and calculates the three-way coincidence distribution (bicovariance) among the signals from a timed source and two detectors.

## SIMULATION OF SOURCE-TWO DETECTORS BICOVARIANCE: CF-252 SOURCE AND TWO SCINTILLATORS

A simple experiment was simulated using MCNP-PoliMi to illustrate the capabilities of the post-processing code. A Cf-252 source was placed between two plastic scintillators, having dimensions 10 by 10 by 10 cm, at a distance of 100 cm from each. A sketch of the experimental setup is shown in Fig. 1. In the simulation, it is assumed that the times of spontaneous fission of the Cf-252 are known. Experimentally, the timing can be measured by placing the Cf-252 inside an ionization chamber, which produces a pulse by detecting the fission fragments. At each spontaneous fission, an average of 3.8 neutrons and 7 gamma rays are emitted promptly, essentially at the same time. A contribution to the bicovariance is made when the two scintillators register a count within a given time window from the signal from the source. In this case, the time window was set to 100 ns.

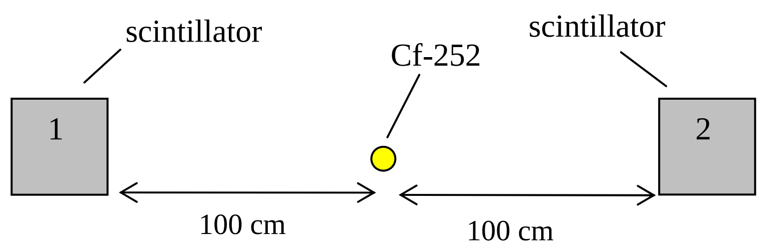



Figure 1. Sketch of the configuration for the simulation of the source-detectors bicovariance function (not to scale).

Figure 2 shows the simulated Cf-252 source and two detectors bicovariance function for the configuration shown in Fig. 1. The Cf-252 spontaneous fission occurs at time lag zero; the time lags to detections in each of detectors 1 and 2 are given in the *x* and *y* axis of Fig. 2. Four features are prominent: a sharp peak centered around time lag 3.3 ns, two symmetric distributions along each of the time axes, and a broad distribution in the region between time lags 25 and 70 ns. These four features can be analyzed by using the post-processing code to split the bicovariance according to what particle was detected at each of the two detectors, as shown in the contour plots in Fig. 3.

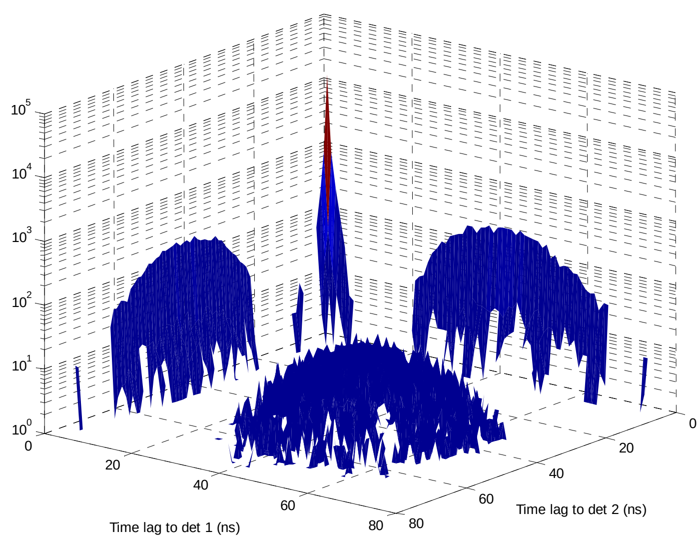



Figure 2. Simulation of source-detectors bicovariance: total signature.

The four possible combinations of detector 1 – detector 2 counts are: photon-photon (Fig. 3 (a)), neutron-neutron (Fig. 3 (b)), neutron-photon (Fig. 3 (c)), and photon-neutron (Fig. 3 (d)).

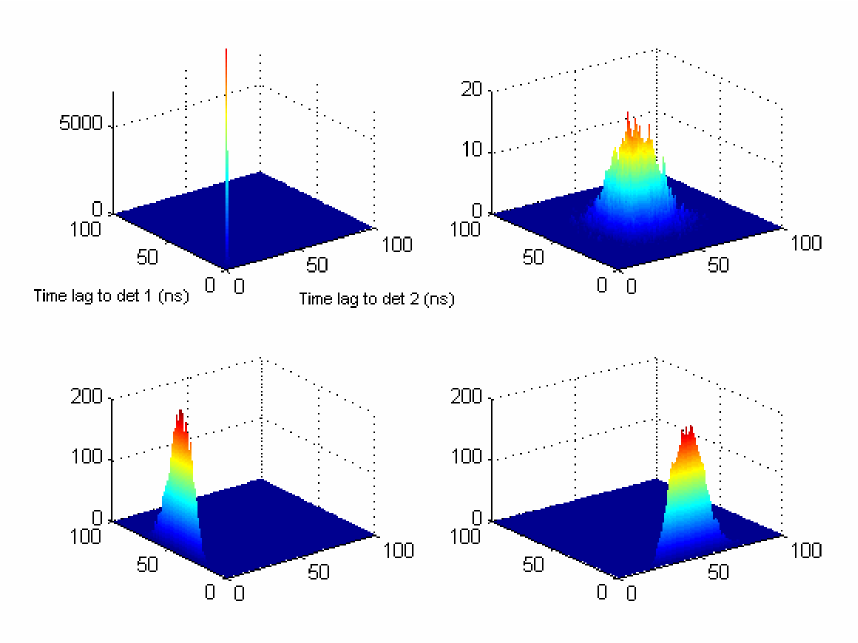



Figure 3. Simulation of source-detectors bicovariance: (a) photon-photon pairs, (b) neutron-neutron pairs, (c) neutron-photon pairs, and (d) photon-neutron pairs.

The contributions to the bicovariance due to different particle types occur at time lags that are consistent with the time-of-flight of the particles from the source to the detectors. For example, the photon-photon contribution shown in Fig. 3 (a) appears at a time lag of 3.3 ns because photons travel at the speed of light. Fig. 3 (b) shows the neutron-neutron contributions to the bicovariance, which appear at time lags between 25 and 70 ns, approximately. The neutron-photon contributions have a distribution of delays for the neutrons and a short delay (3.3 ns) for the photons (Fig. 3 (c) and (d)).

**SIMULATION OF SOURCE-TWO DETECTOR BICOVARIANCE: FISSILE MATERIAL**

The measurements considered in this paper were developed to investigate nondestructively the properties of fissile samples for safeguards, non-proliferation, and accountability purposes [5]. Monte Carlo methods have proven to be a useful tool in the design and analysis of these measurements. The following example illustrates one of the capabilities of the MCNP-PoliMi code and the post-processing code. The simulated configuration is analogous to the one given in the previous section, with the addition of a highly enriched uranium metal sphere, having radius 5 cm, which is placed surrounding the Cf-252 source. The presence of fissile material serves to illustrate the ability of the code to distinguish particles from Cf-252 source events from particles originating in the fission chains induced in the uranium metal.

The total simulated bicovariance for this configuration is given in Fig. 4. The contributions to the bicovariance according to particle type are given in Fig. 5. Comparison of Fig. 4 with Fig. 2 shows the attenuation of the Cf-252 particles by the uranium metal. The production of induced fission particles from fission chains in the uranium metal causes a smearing in all of the regions of the bicovariance signature. This effect is particularly evident in the photon-photon pairs (Fig. 5 (a)).

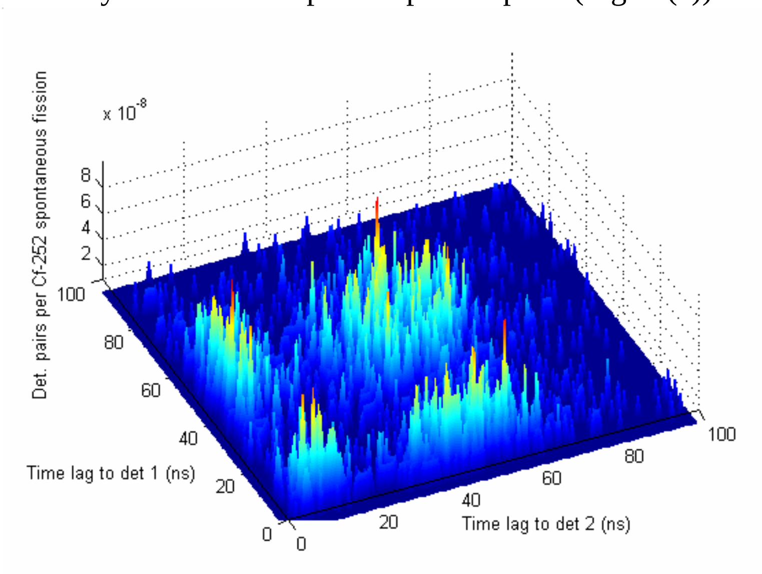



Figure 4. Simulation of source-detectors bicovariance: total signature.

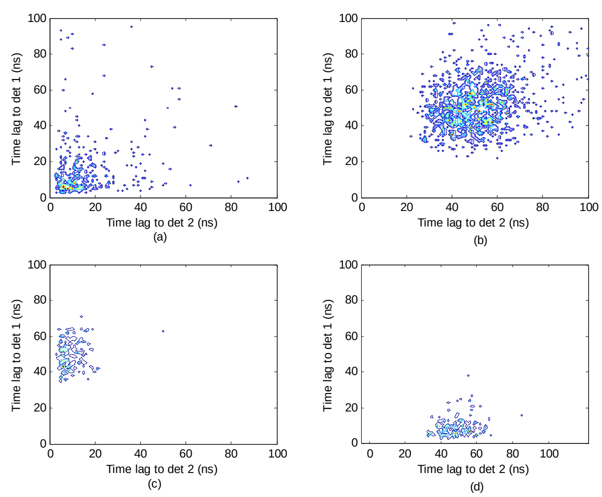



Figure 5. Simulation of source-detectors bicovariance with fissile material: (a) photon – photon pairs, (b) neutron – neutron pairs, (c) neutron – photon pairs, and (d) photon – neutron pairs.

The MCNP-PoliMi output also contains information on the generation number of the particles that are being tracked. In our nomenclature, 'generation zero' particles are particles that come from the source, and particles that have been generated by source particles by all interactions except for fission. 'Induced fission' particles are particles that come from the fission induced in the fissile material. A split of the bicovariance can be performed according to the generation of the particles that are detected in the detectors. Four possible pairs of events can occur: generation zero – generation zero, induced fission – induced fission, generation zero – induced fission, and induced fission – generation zero. These contributions are shown in Fig. 6.

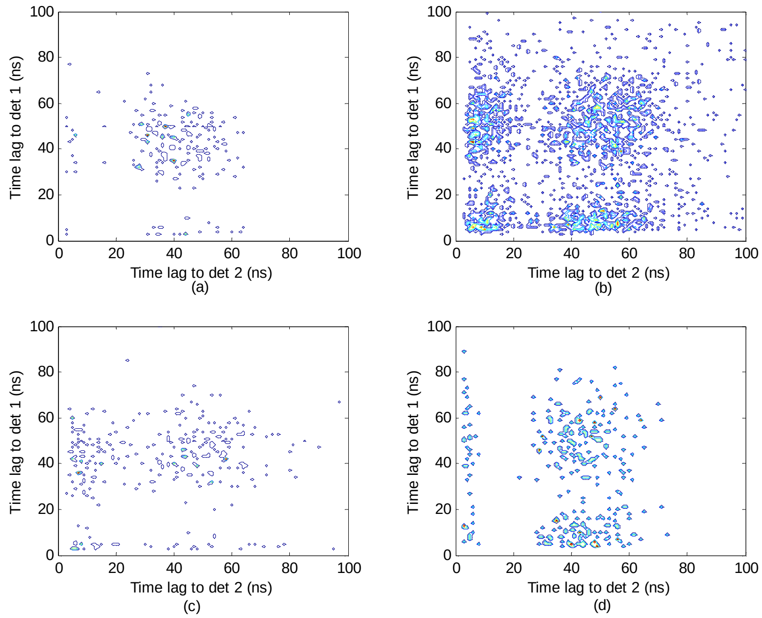



Figure 6. Simulation of source-detectors bicovariance with fissile material: (a) generation zero – generation zero pairs, (b) induced fission – induced fission pairs, (c) generation zero – induced fission pairs, and (d) induced fission – generation zero pairs.

Comparison of Fig. 6 (a) and Fig. 6 (b) shows that there is a greater contribution to the bicovariance from pairs of induced fission particles than from pairs of generation zero particles. For this particular configuration, the ratio of the number of total induced fission pairs to the number of total generation zero pairs is approximately 10.

## COMPARISON WITH EXPERIMENTAL DATA

A comparison is presented between experimental data acquired with the Nuclear Materials Identification System and simulated data. The measurements and simulations were performed for assemblies of plutonium shells of varying inner and outer diameter. A sketch of the measurement configuration is given in Fig. 7. Further details on the experiments and their simulation are given elsewhere [7-8].

Figure 8 shows the comparison of the measured source-two detector bicovariance for a plutonium metal shell (98% Pu-239) having mass 4.0 kg, outer radius 6.0 cm and inner radius 5.35 cm. Comparison of Fig. 8 (a) and (b) shows that the four regions of the bicovariance are well represented in the simulated signature.

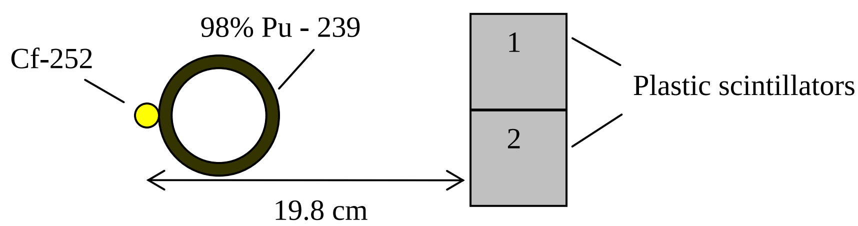
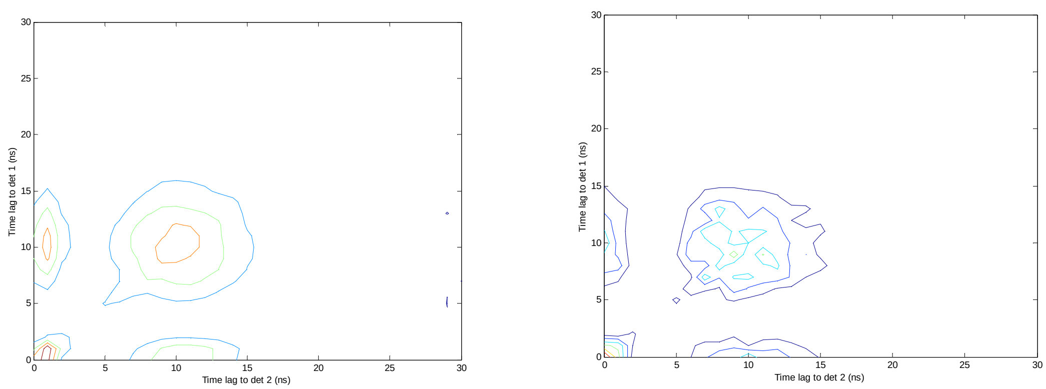



Figure 7. Sketch of the configuration for the simulation of the source-detectors bicovariance function with plutonium sample (not to scale).




(a) (b)

Figure 8. Source-detectors bicovariance with plutonium sample: (a) Experimental result and (b) MCNP-PoliMi simulation.

Figure 9 shows a split of Fig. 8 (b) performed according to generation of the particles pairs detected by the scintillators. Integration of the surfaces given in Fig. 9 reveals the total number of detected pairs per Cf-252 source fission. The number of pairs (Fig. 9 (a)) given by generation zero particles is 5.5 $10^{-4}$. The number of pairs given by induced fission particles (Fig. 9 (b)) is 3.18 $10^{-4}$. The remaining pairs are given by combinations of generation zero particles and induced fission particles (Fig. 9 (c) and (d)), for a total of 1.93 $10^{-4}$.

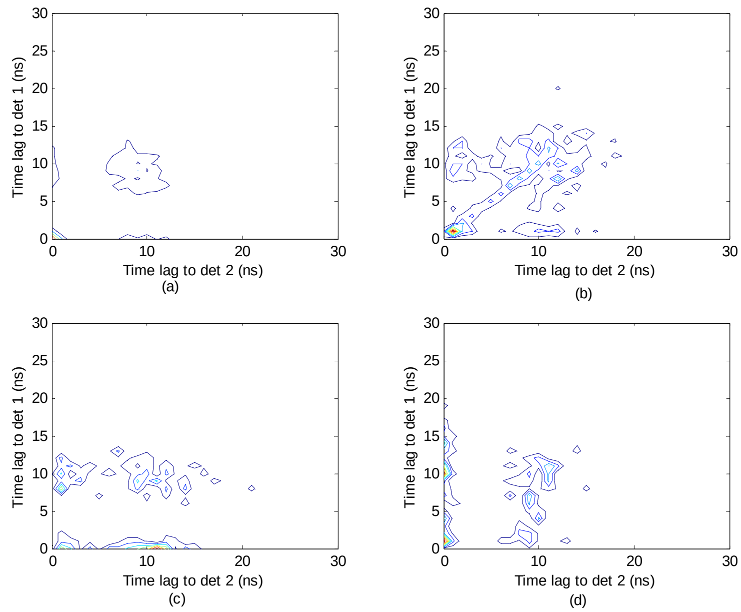



Figure 9. Simulation of source-detectors bicovariance with plutonium sample: (a) generation zero – generation zero pairs, (b) induced fission – induced fission pairs, (c) generation zero – induced fission pairs, and (d) induced fission – generation zero pairs.

## CONCLUSIONS

This paper presented the capabilities of a post-processing code developed to simulate third order statistical signatures, to be used in conjunction with the MCNP-PoliMi data output. The source-two detector bicovariance functions were simulated in two simple cases. In the first, a Cf-252 source and two scintillators were modeled, and in the second a uranium metal sample was added. The second example had the objective of describing the ability of the code to perform a split of the bicovariance according to the generation of the particles detected. This capability is useful in the evaluation of sources for the interrogation of fissile samples for safeguards, non-proliferation, and accountability purposes. A comparison between a source-detectors bicovariance function for a measurement on a plutonium metal shell and the simulation was also given.

## ACKNOWLEDGMENTS

The authors would like to thank Vitaliy Dubinin and colleagues of the Russian Federal Nuclear Center, All-Russia Scientific Research Institute of Experimental Physics, for making available the data taken with NMIS on the plutonium assembly.

## REFERENCES

[1] S. A. Pozzi, E. Padovani, and M. Marseguerra, "MCNP-PoliMi: A Monte Carlo Code for Correlation Measurements," Nuclear Instruments and Methods in Physics Research A, 513/3 pp. 550-558.

[2] J. F. Briesmeister, Ed., “MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C,” LA-13709-M, Los Alamos National Laboratory (April 2000).

[3] J. K. Mattingly, *High Order Statistical Signatures from Source-Driven Measurements of Subcritical Fissile Systems*, doctoral dissertation, University of Tennessee, Knoxville, August, 1998.

[4] M. Marseguerra, E. Padovani, S.A. Pozzi, and M. Da Ros “Phenomenological Simulation of Detector Response for Safeguards Experiments,” Nuclear Instruments and Methods B, 213 pp. 289-293, 2004.

[5] J. T. Mihalczo, J. A. Mullens, J. K. Mattingly and T. E. Valentine, “Physical description of nuclear materials identification system (NMIS) signatures,” Nuclear Instruments and Methods in Physics Research A, 450/2-3, pp. 531-555, 2000.

[6] S. A. Pozzi, R. B. Oberer, L. G. Chiang, J. K. Mattingly, and J. T. Mihalczo, “Use of Higher Order Statistics to Determine Neutron and Gamma Ray Cross Talk in Plastic Scintillators,” Nuclear Instruments and Methods in Physics Research A 481/1-3 pp. 739-748, 2002.

[7] J. K. Mattingly, J. T. Mihalczo, L. G. Chiang, and J. S. Neal, “Preliminary Analysis of Joint RFNC-VNIIEF/ORNL Measurements Performed In Year 2000,” Y/LB-16,097, Y-12 National Security Complex, September 2001.

[8] S. A. Pozzi, J. K. Mattingly, J. T. Mihalczo, and E. Padovani, “Validation of the MCNP-PoliMi Code for the Simulation of Nuclear Safeguards Experiments on Uranium and Plutonium Metal,” Nuclear Mathematical and Computational Sciences: A Century in Review, a Century Anew, Gatlinburg, Tennessee, April 6-11, 2003, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2003).