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3D Image Reconstruction from Correlated Events of Gamma-Neutron Sources

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Abstract – We describe a new method of 3D reconstruction of correlated neutron sources, including all Special Nuclear Materials (SNM). As an alternative to multi-view reconstruction, this technique uses an intrinsic property of the source; specifically that emitted gammas and neutrons are correlated (e.g. Cf-252, Am-Be). In principle, any imaging detector sensitive to gammas and neutrons with adequate timing resolution can used to perform this reconstruction. Using a neutron double scatter technique, we can constrain the source in two-dimensions through back-projection. By including the time to a correlated gamma we further constrain the source location in three-dimensions by solving for the source-to-detector distance. The incident neutron energy is estimated as the sum of energy deposited in the first scatter and time-of-flight (TOF) to a second interaction. Using this energy, the time between the arrival of a correlated gamma and incident neutron, and knowledge that the gamma-ray travels the speed of light, the source location can be constrained in three-dimensions. As a proof of concept we applied the proposed reconstruction technique on data taken with the Mobile Imager of Neutrons for Emergency Responders (MINER) and found that sources 10 cm apart were able to be resolved with depth FWHM of ~20 cm. Simulations results show that with 200 ps timing and 5 mm interaction location resolution the depth reconstruction resolution improves down to FWHM of 5 cm.

Motivation and Objectives

Motivation

- Imaging of SNM has multiple useful applications from emergency response, warhead confirmation, and facility inspection.
- The standard method a 3D image reconstruction, in both optical and radiological application, relies on taking multiple images of an object of interest from multiple-views.
- In certain scenarios, such as inspection, multiple views of the object may be unavailable.

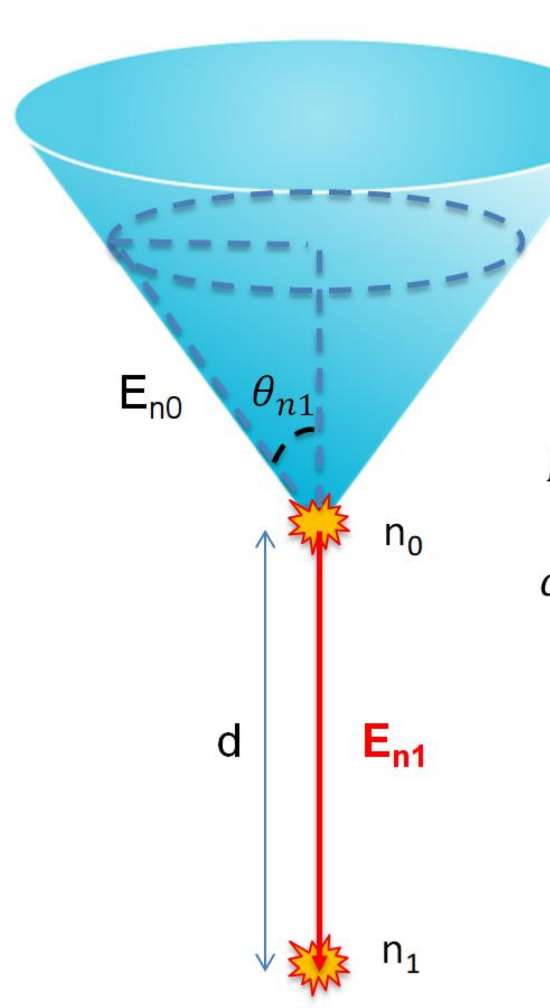
Objectives

- Develop a method for single-sided 3D image reconstruction of sources that emit correlated gammas and neutron..
- Test the method using a compact neutron double scatter camera MINER.
- Improve image reconstruction using Stochastic Origin Ensembles (SOE) approach based on Markov chains.
- Evaluate image resolution performance as a function of measurement system properties, such as better timing and interaction localization, through simulation.

Method

Neutron double scatter imaging (2D)

- It is possible to reconstruct a cone of possible source location from a detected neutron double scatter (typically in two separate detector cells) using:
  - E_d: Energy deposited in first scatter
  - $\Delta t_{n_0,n_1}$: The time-of-flight between two scatters.
- From which it is possible to calculate:
  - θ_{n1}: Opening angle of a cone with vertex on the first scatter pointing in the direction of a vector between two scatters.
  - E_{n0}: Energy of incident neutron.



$$E_{n1} = \frac{m_n}{2}\left(\frac{d^2}{\Delta t_{n_0,n_1}}\right)$$

$$E_{n0} = E_d + E_{n1}$$

$$cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

Fig. 1. Cone of possible source locations based on neutron double scatter.

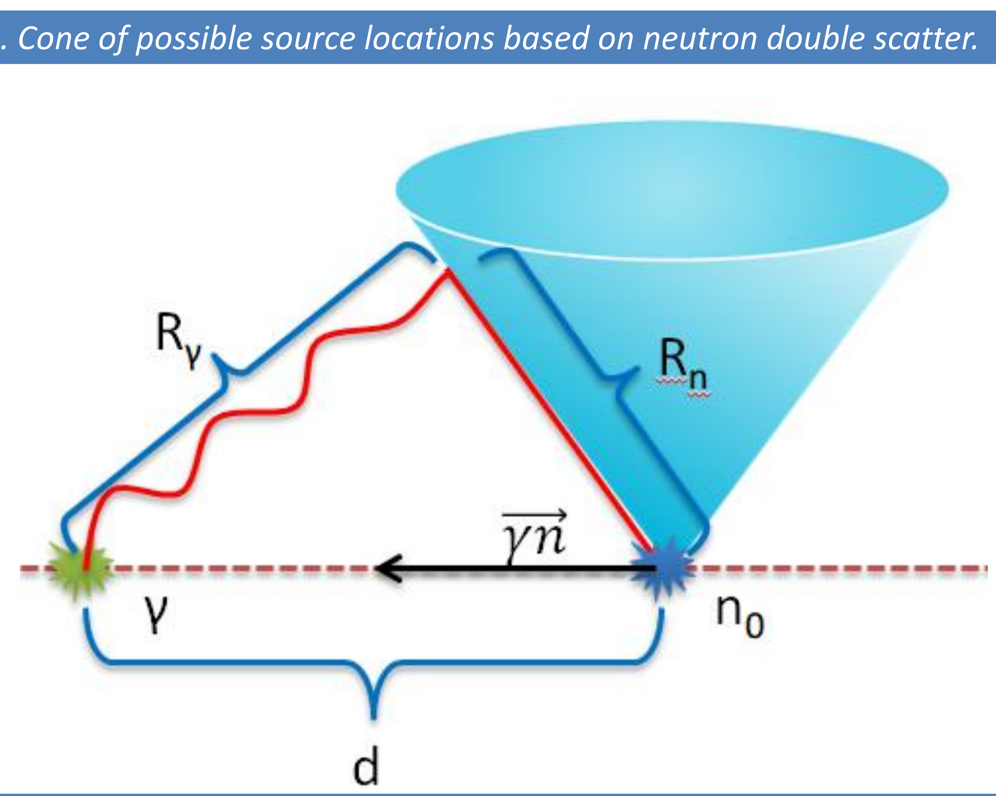


Fig. 2. Double scattered neutron (only first scatter shown) with a correlated gamma. The addition of a correlated gamma allows the source location to be constrained in the third dimension along the surface of a cone.

Neutron scatter imaging with correlated gamma (3D)

- In addition to the quantities measured with neutron double scatter, the correlated gamma provides the time between first neutron scatter and gamma:

$$\Delta t = \frac{R_n}{v_n} - \frac{R_\gamma}{c}$$

- The geometric relationship between these quantities is depictured in Figure 2. Using the law of cosines we can express another relationship between distances from the source to interaction points (R_n and R_γ) as a function of the cosine of the angle (μ) between the cone surface and the vector $\overrightarrow{\gamma n}$:

$$R_\gamma^2 = R_n^2 + d^2 - 2R_n d\mu$$

- Finally we can use Eq. (1) and (2) to solve for the desired distance R_n along the length of the cone:

$$R_n = \frac{c^2\Delta t v_n - d v_n^2 \mu + \sqrt{v_n^2 c^2 \left(\Delta t^2 v_n^2 - 2dv_n\mu\Delta t + d^2\right) + v_n^2 d^2\left(\mu^2 - 1\right)}}{c^2 - v_n^2}$$

- This is a solution to a quadratic equation, but only one solution is valid because $v_n < c$.
- We will have a different R_n solution for every azimuthal angle along the surface of a cone. Therefore our final reconstruction for a single event will resemble a "donut" in space as shown below in Figure 3.

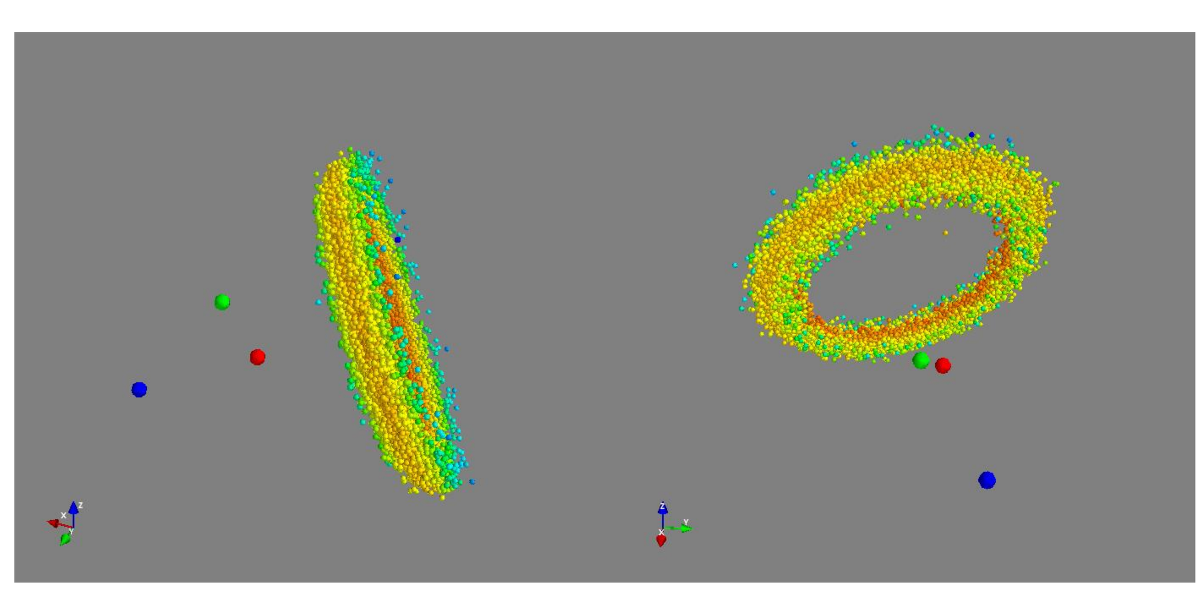


Fig. 3. Possible source locations based on a single event reconstruction from double scattered neutron (red and blue) and a correlated gamma (green).

Stochastic Origin Ensembles

- In an effort to improve the image reconstruction we employed SOE, which can be implemented in the following manner:
  1. Source origins are randomly sampled for each event from possible source locations (the "donut").
  2. PDF is constructed based on source origins.
  3. New source origins are sampled and are accepted based on change in event density.
  4. Iteration continues until a sufficient number of points were sampled to accurately reflect the "true" underlying source PDF.
- Due to the small number of total correlated events in our measurement (~6000), we used Kernel Density Estimator (KDE) instead of a histogram which would otherwise be quite sparse.

Measurement and Simulation

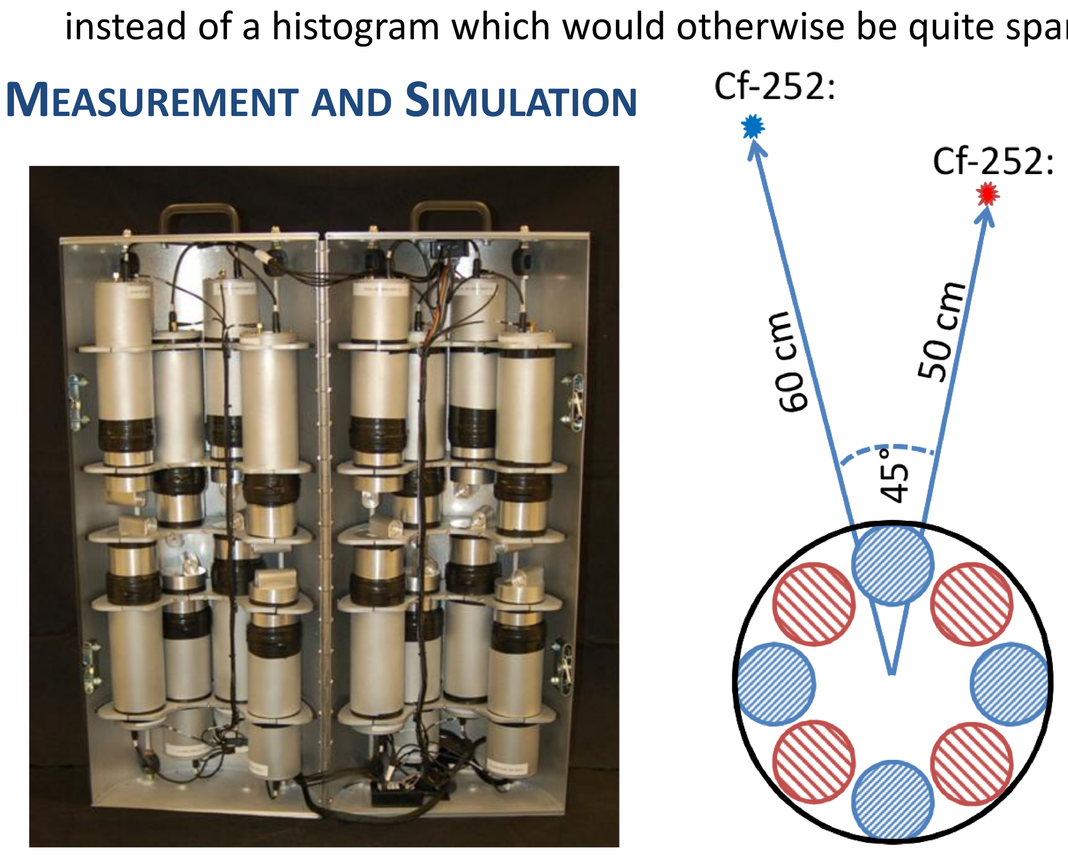


Fig. 4. MINER system (left) and measurement setup (right) of the two Cf-252 sources measured.

Results

- Using MINER we were able to resolve the two sources located 10 cm apart, SOE was implemented which eliminated some of the artifacts from back-projection.
- Simulation of MINER with improved timing (200 ns) and interaction location (5 mm) resolutions achievable with next generation system.

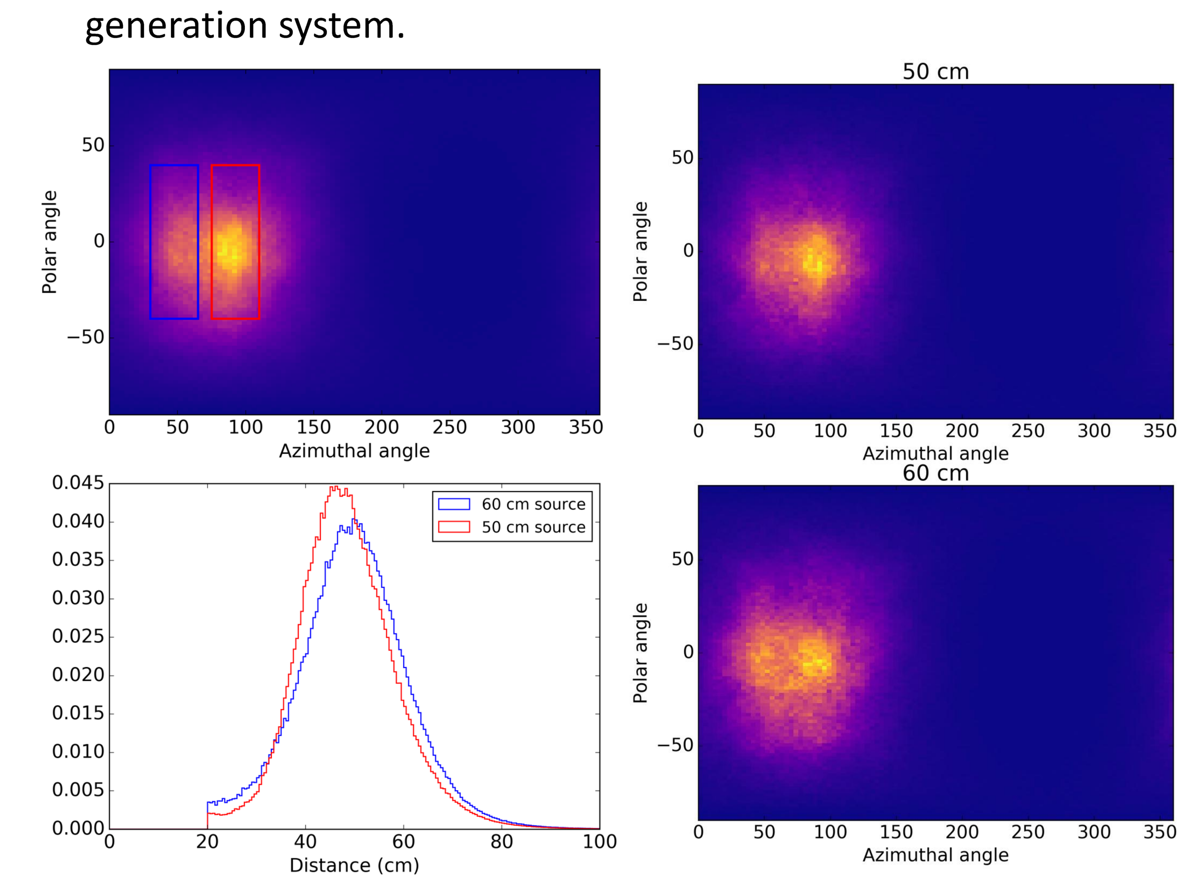


Fig. 5. Measurement of the two Cf-252 sources with MINER reconstructed with the help of SOE. The figure on the left shows the depth estimation of each of the boxed in regions on the image. The figure on the right is a representative 10 cm slice of the image centered around 50 cm and 60 cm.

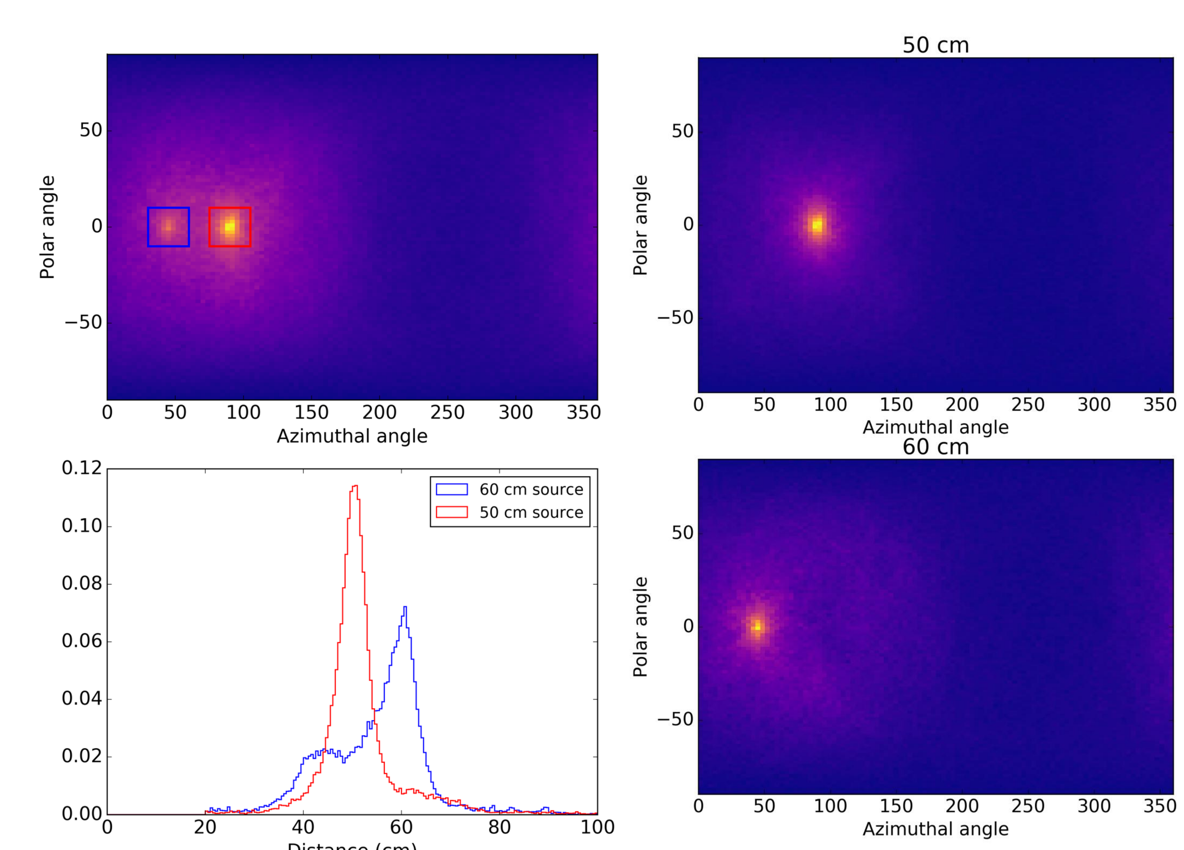


Fig. 6. Simulation of the MINER system with assumed timing resolution of 200 ps and interaction location resolution on 5 mm. The images are displayed in the same fashion as shown in Figure 5.

Conclusions

- We developed a method for constraining source location to three-dimensions using a neutron double scatter correlated with a gamma. The end result is a "donut" in space for each measured set of events. The method works with single-sided measurement of the source, but is inherently limited to sources that emit gammas and neutrons in coincidence (fissions, (alpha,n)).
- It is possible to resolve sources 10 cm apart using a less than ideal neutron scatter camera (mediocre timing and angular resolution). Nevertheless with the help of SOE it is possible to eliminate some noise and artifacts from back-projection.
- Simulated results show great improvement in depth and angular resolution if the timing and location resolution could be improved. Such improvements could be attainable through the use of faster photo-collector (PMTs or SiPMs). Furthermore the cell geometry and size could be optimized to improve localization resolution while maintaining adequate efficiency.

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