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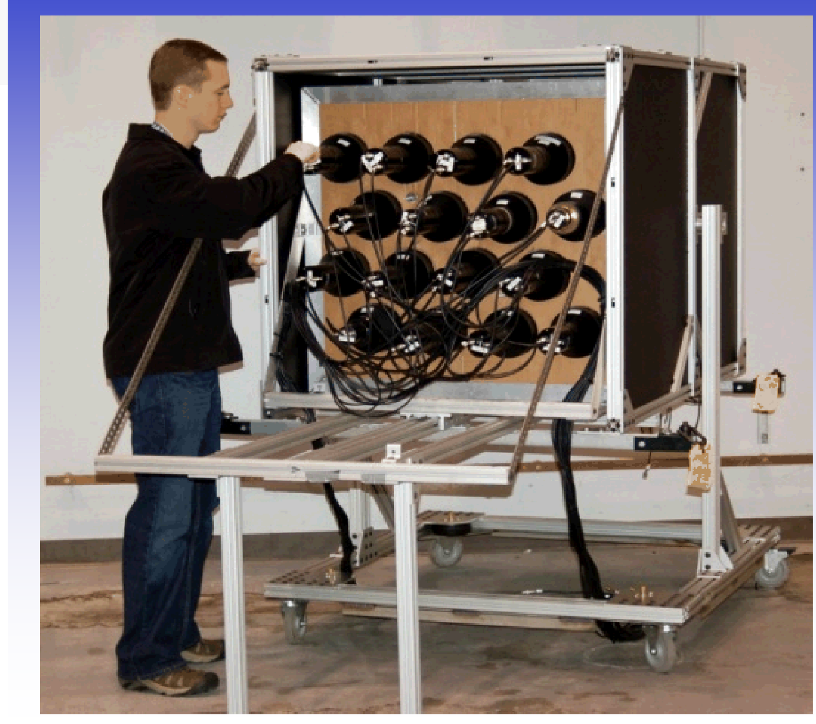
Advanced Image Reconstruction and Source Detection Methods

James Brennan, Erik Brubaker, Robert Cooper, Mark Gerling, Peter Marleau, Nick Mascarenhas, Stan Mrowka, John Steele, Daniel Throckmorton

Sandia National Laboratory, 7011 East Ave, Livermore, CA 94550

Introduction



The neutron scatter camera (NSC) and other fast neutron detectors developed at Sandia National Labs acquire data in various ways that have sensitivity to the incoming direction of the arriving neutron. However, reconstruction of this data into an image understandable by a human is not trivial. We use several different reconstruction techniques, each of which has advantages and disadvantages.

Examples in this poster primarily pertain to the NSC, which is a 32-element liquid-scintillator-based imaging fast neutron spectrometer, pictured at left. As shown in the figure to the right, neutrons that scatter in both the front and rear planes of the NSC supply enough kinematic information that their energies and directions (up to a conical ambiguity) can be determined.

The relevant inputs from the NSC to the image reconstruction algorithms can be boiled down to three independent values: front detector ID, rear detector ID, and the angle θ, calculated from TOF and energy measurements.

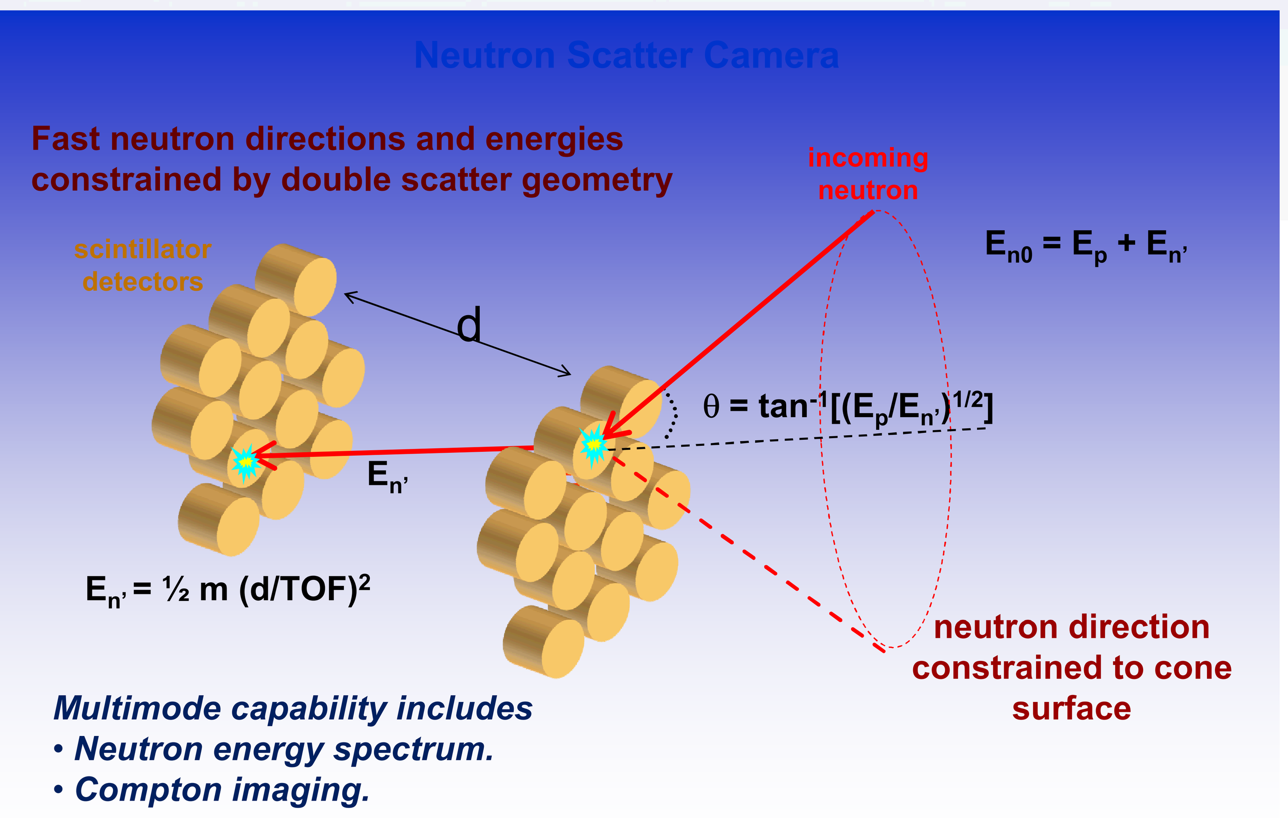
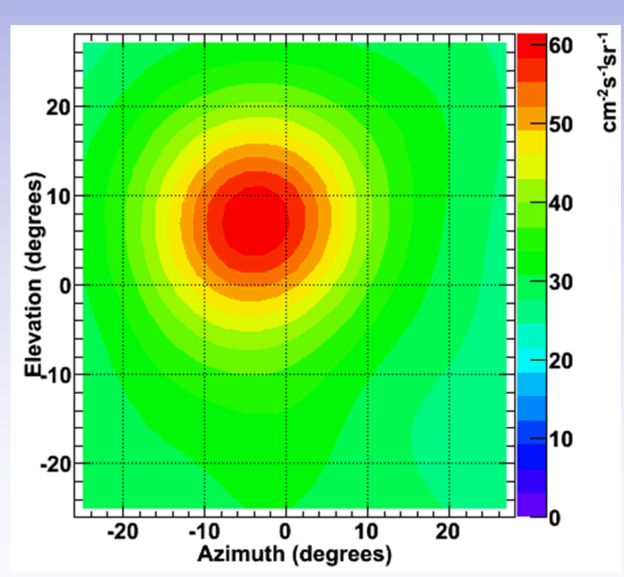


Image Reconstruction

The neutron scatter camera has been applied to image extended sources, which are simulated using a single point source placed on a continuously moving path in a straight line. For the purpose of this exercise, we first imaged one such extended source using a path length of 51cm in the horizontal direction three meters from the camera. Our backprojection and image decoding methods fail to accurately reconstruct such an extended source, but maximum likelihood expectation maximization (MLEM) reconstructions are more accurate.

Backprojection

The backprojection method simply superimposes rings corresponding to the possible source positions for each neutron event. This method is simple and intuitive: over many events, there is an enhancement where many rings overlap, corresponding to the true source position. However, the resolution of the source distribution is limited by the resolution of a single event, and misreconstructed events are not easy to account for.

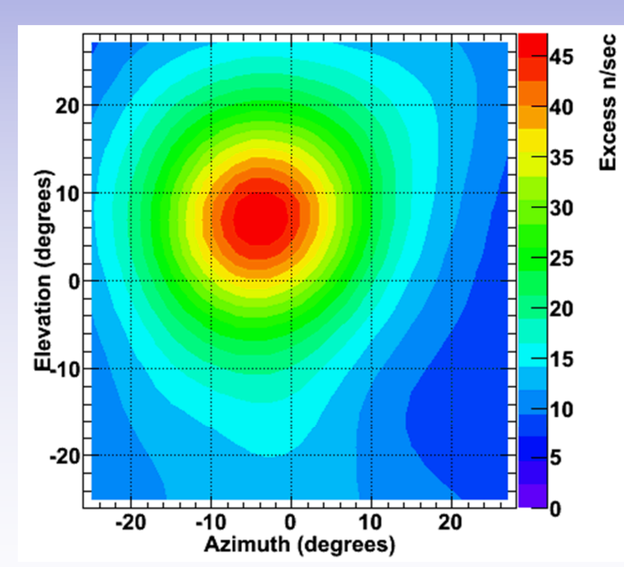


Pros:
- Fast & simple.
- Easy to explain.

Cons:
- Resolution limited by single-event properties.
- Difficult to account for misreconstructed events.

Image Decode

The image decode method was developed at SNL as a modification of standard backprojection. By analogy with coded aperture image reconstruction, the decode method attempts to sharpen the image by subtracting from each pixel a baseline quantity determined by summing events whose rings do not contribute to signal in the pixel.

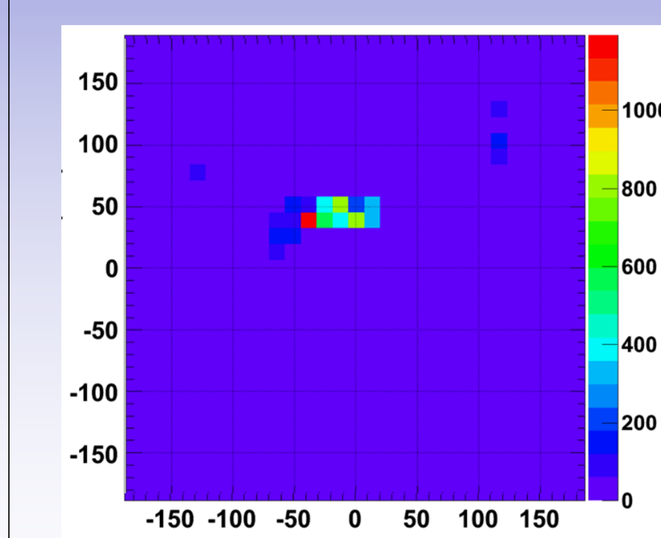


Pros:
- Removes "baseline" background.
- Relatively fast.

Cons:
- Ad hoc algorithm.
- Still resolution limited.

MLEM

Maximum Likelihood Expectation Maximization is a mature iterative image reconstruction technique originally developed in the context of medical imaging. Based on a thoroughly described system response matrix, and through an algorithm based on Poisson statistics, the space of source distributions is searched for the one most likely to produce the observed data. In MLEM reconstruction, the resolution is limited by √N statistics (either of the data or the system response matrix), so super-resolution can be achieved. Misreconstructed events can be accounted for in the response matrix . Drawbacks include large computing power and time requirements, as well as the need for regularization terms to control the effect of statistical fluctuations on the image.



Pros:
- By construction, most accurate estimate of source distribution.
- System response matrix can account for arbitrarily complex effects.

Cons:
- Slow.
- Requires an accurate response matrix → more CPU time.
- Need stopping condition.

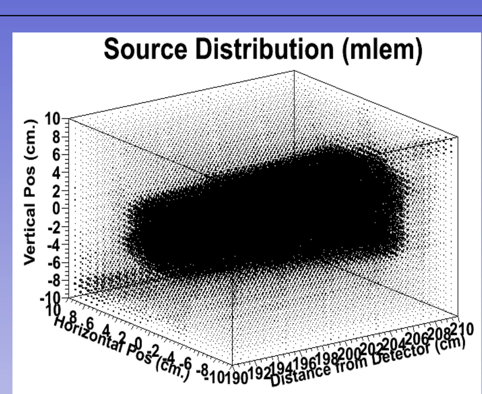
3-D from Multiple Views

Most radiation imagers are primarily concerned with imaging in a two-dimensional projection onto the field of view. Depth perception is usually limited to distances of the order of the transverse extent of the imager. When the full three-dimensional source distribution is of interest, a useful technique is to integrate information from multiple views of the same object. The multiple views can be acquired by rotating the target object, or by changing the location of the imager with respect to the object.

In the context of MLEM image reconstruction, the multiple views can share a source space, but occupy different sub-spaces of the observation space. In this way, a single MLEM reconstruction merges information from both views to reconstruct the three-dimensional image.

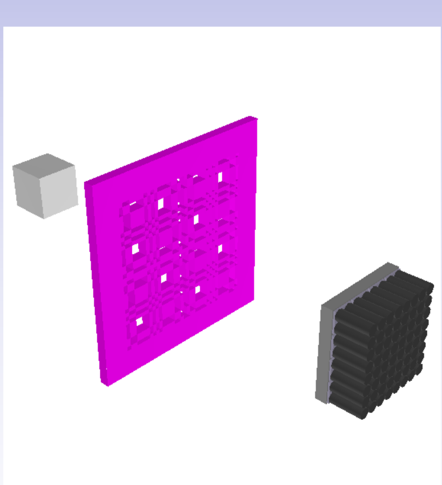
Simulated example:

Inspection object (PuAl, DU) imaged with a fast neutron coded aperture imager.

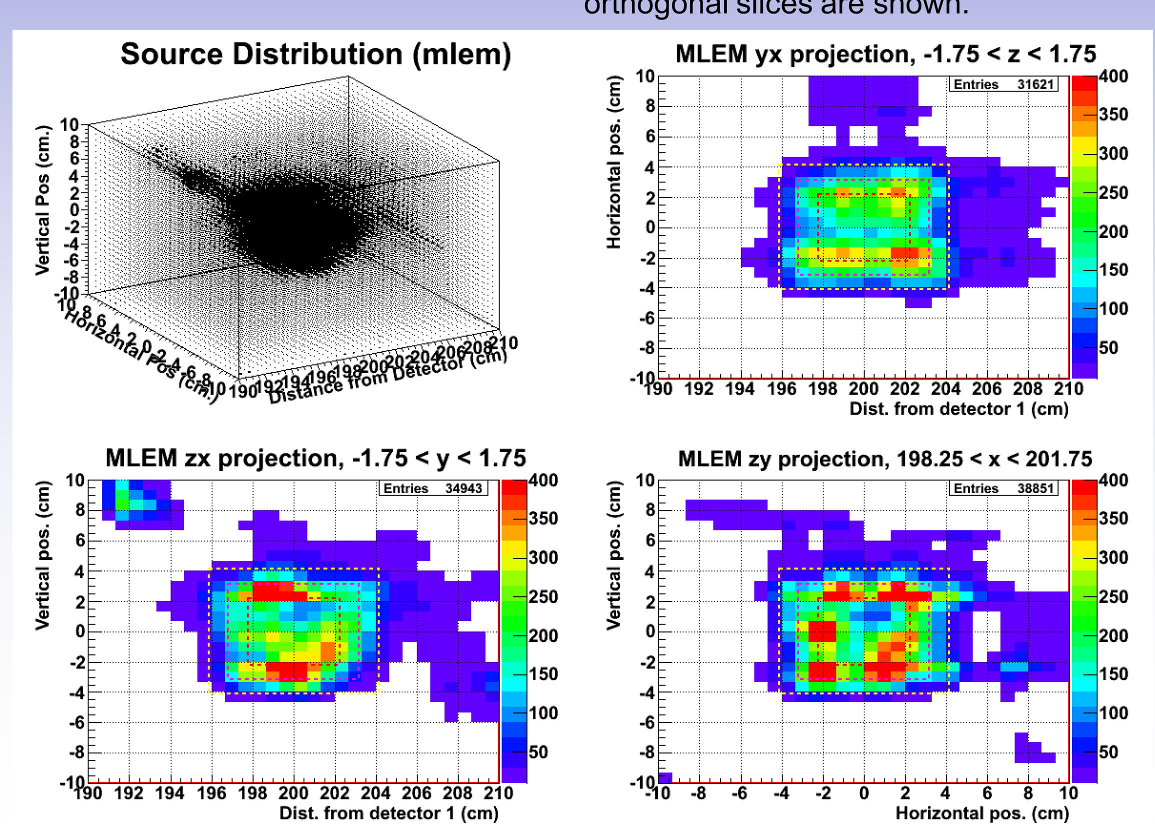


Left: Three-dimensional reconstruction of a simulated inspection object with cubical symmetry using a single view. Depth perception is almost non-existent.

Below: The same simulated object and reconstruction method (MLEM), but with two orthogonal viewing positions. The object is well localized in three dimensions. Projections on three orthogonal slices are shown.



Simulation geometry using the Neutron Coded Aperture Imager (ORNL/SNL).



Hypothesis Test

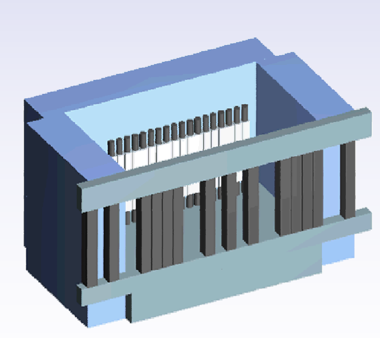
For certain applications, an image is not the end goal. An example is a search for low-strength radioactive sources in surrounding background, where the desired output is an alarm decision, not an image per se. In such cases, imaging can in fact be counter-productive, since it necessarily introduces noise and enhances statistical and systematic variations in the data. A more appropriate approach is task-based imaging, where the data as detected is mined for answers to specific questions.

The hypothesis test is one task-based technique, developed to optimally detect the presence of a point source in a background field.

- **Theory:**
  - **If signal and background behavior are known, the likelihood ratio is a sensitive test statistic to distinguish between them.**
  - **By definition, encodes probability of statistical fluctuations.**
  - **Systematic uncertainties can be accounted for as nuisance parameters.**
    - Integrate over them: Bayesian.
    - Fit for most likely (given constraints): Frequentist.

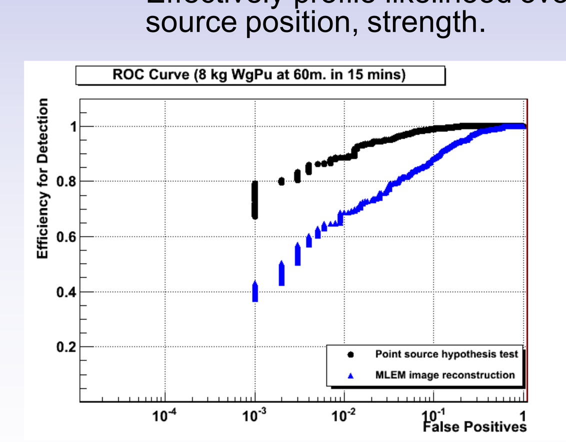
$$LLR = \ln \frac{L(\text{data} \mid s+b)}{L(\text{data} \mid b)}$$

- **Assumptions:**
  - The background is known.
    - *Can be relaxed later by introducing background systematics.*
  - The relevant signal is a *single* point source within the field of view.
    - *Restricting the hypothesis space to a single point source "sharpens" the hypothesis test and reduces false alarms.*
    - *Should be valid in the vast majority of cases; algorithm performance may still be acceptable in outlier scenarios.*



The 1-D coded aperture neutron imaging system used for this demonstration

- **Procedure:**
  - **Loop over possible point source locations (in field of view).**
  - **For each source position, find LLR = Δ(ln L) between b-only and s+b hypotheses.**
    - Signal strength is unknown, so maximize LLR over signal fraction f:
    - $LLR = \max_f(\ln L(\text{data}|n_s=fN) - \ln L(\text{data}|n_s=0))$.
  - **The largest LLR obtained from any potential source position is the test statistic.**
    - Effectively profile likelihood over source position, strength.



ROC curve showing enhanced sensitivity using hypothesis test vs a threshold on the max bin content in an MLEM image.

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