Oak Ridge National Laboratory

Application of SCALE/Sampler and MAVRIC to Nuclear Safeguards and Security

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"Uncertainty Analysis For Neutron Active Interrogation Calculations" ANTPC 2018

Outline

- Background
- MAVRIC Model
- Sampler Model
- Review of Sampler Results and Analysis
- Conclusions

Background

- Active Interrogation: radiation is directed into a container suspected of carrying special nuclear material. The products of any subsequent fission reactions are then detected.

- Active vs Passive Interrogation

Method	Pros	Cons
Active Interrogation	**High-energy radiation can penetrate far into a container.**	**Requires the presence of an activation source.**
Passive Interrogation	**Uses natural radiation emitted from SNM.**	**Low-energy radiation that is easily attenuated within the container.**

- Current neutron activation systems include the active well coincidence counter (AWCC) and the uranium neutron coincidence collar (UNCL)

- **Motivation for this study: How does input uncertainty impact our decisions on the use of active interrogation in the field?**

Simulation of Active Interrogation Problems

- Active interrogation simulation presents unique challenges
  - Only a small fraction of the simulated source particles reaches the SNM to cause fission.
  - Only a small fraction of the fission signature radiation reaches the detectors.
    - *Calculations require very long computation times to reduce uncertainties to acceptable levels.*
- Run times can be significantly reduced with automated variance reduction techniques.
  - The MAVRIC sequence is used to create space- and energy-dependent importance parameters.

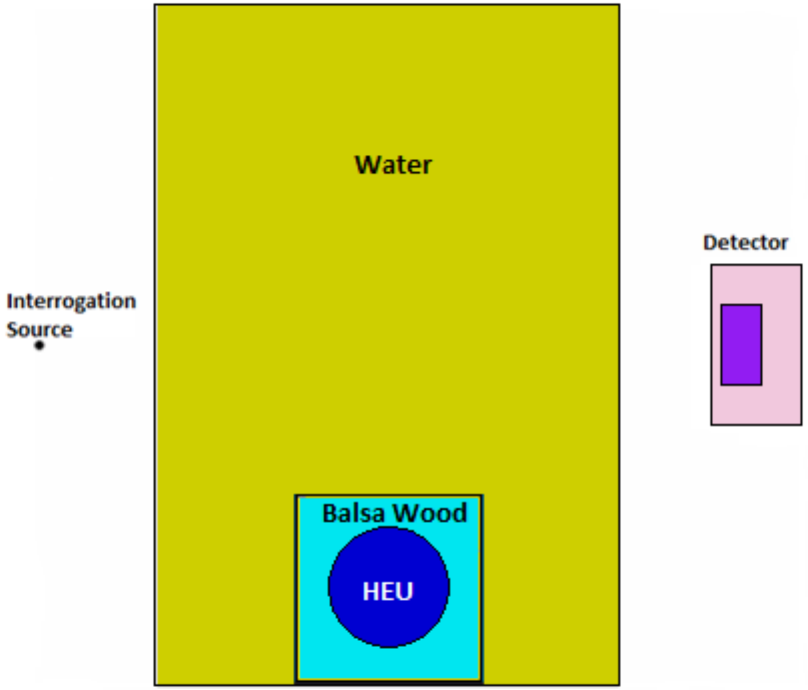
A two-step approach to biasing*

- Biasing is needed in two parts of the simulation.
  - Interrogation source particles are biased to increase interaction with the SNM.
  - Fission particles are biased to increase interaction with the detector.
    - *Current transport simulation capabilities do not handle this dual biasing.*
- To overcome the limitations of the solvers, two steps were used:
  - Step 1: Particles are transported from the interrogation source to the SNM. The fission particles produced become the sources for Step 2.
    - The fission source needs to be well characterized in space and energy.
  - Step 2: Calculate the detector response to the source generated in Step 1 and the interrogation source.
  - In each step, importance maps are created using MAVRIC's CADIS (Consistent Adjoint-Driven Importance Sampling) method.
- This approach was shown to produce a ~200x speedup (390 hrs to 2 hrs).

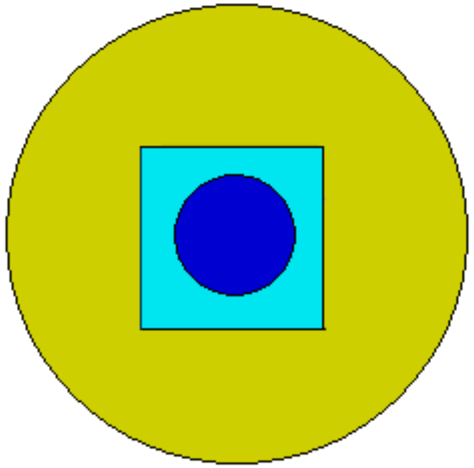
*Peplow et al., "Hybrid Monte Carlo Deterministic Methods for Accelerating Active Interrogation Modeling," *Nuclear Technology*, **182**, 63-74 (2013).

MAVRIC Model

- Active interrogation model:
  - A 55-gallon barrel is filled with water and a 25 kg HEU sphere.
    - The sphere is encased within a box of balsa wood to prevent criticality.
  - The D-T interrogation source isotropically emits 14.1 MeV neutrons.
  - On the opposite side of the barrel is a polyethylene-moderated helium-filled detector.



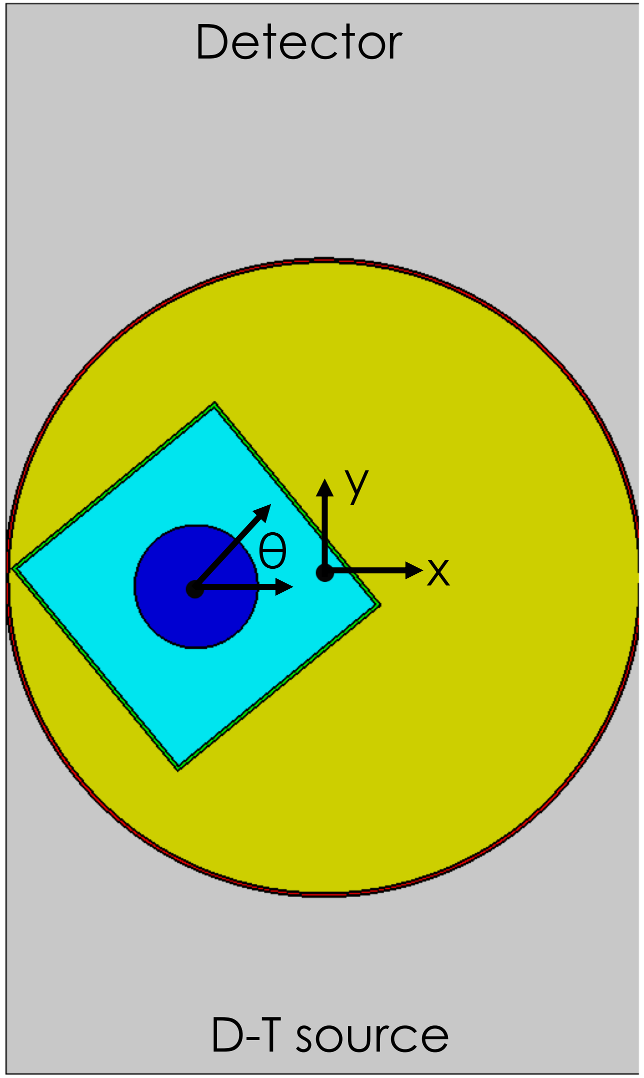
Side View

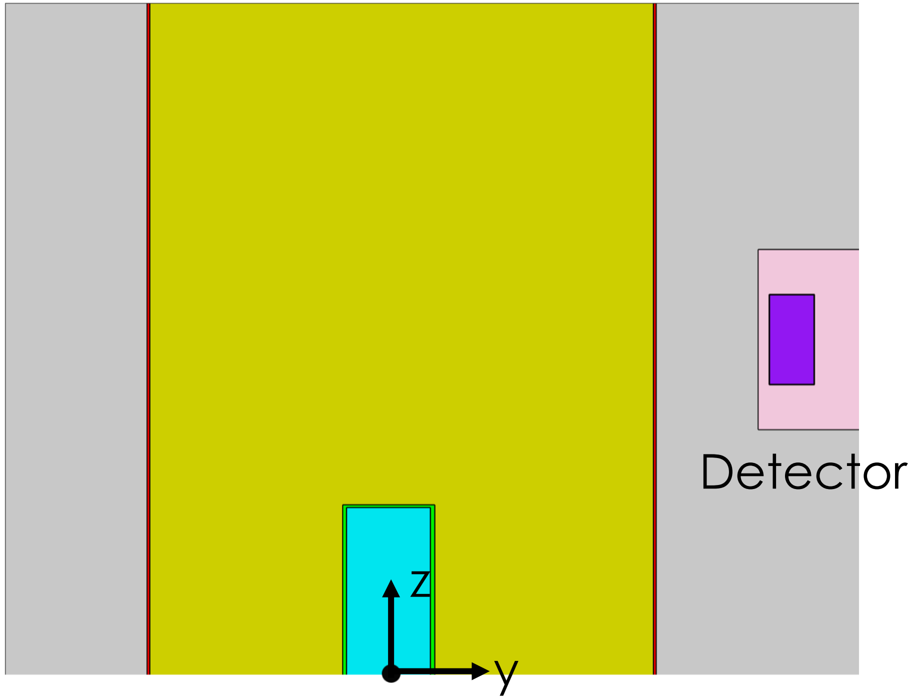


Top View

How does geometry uncertainty impact active interrogation analysis?

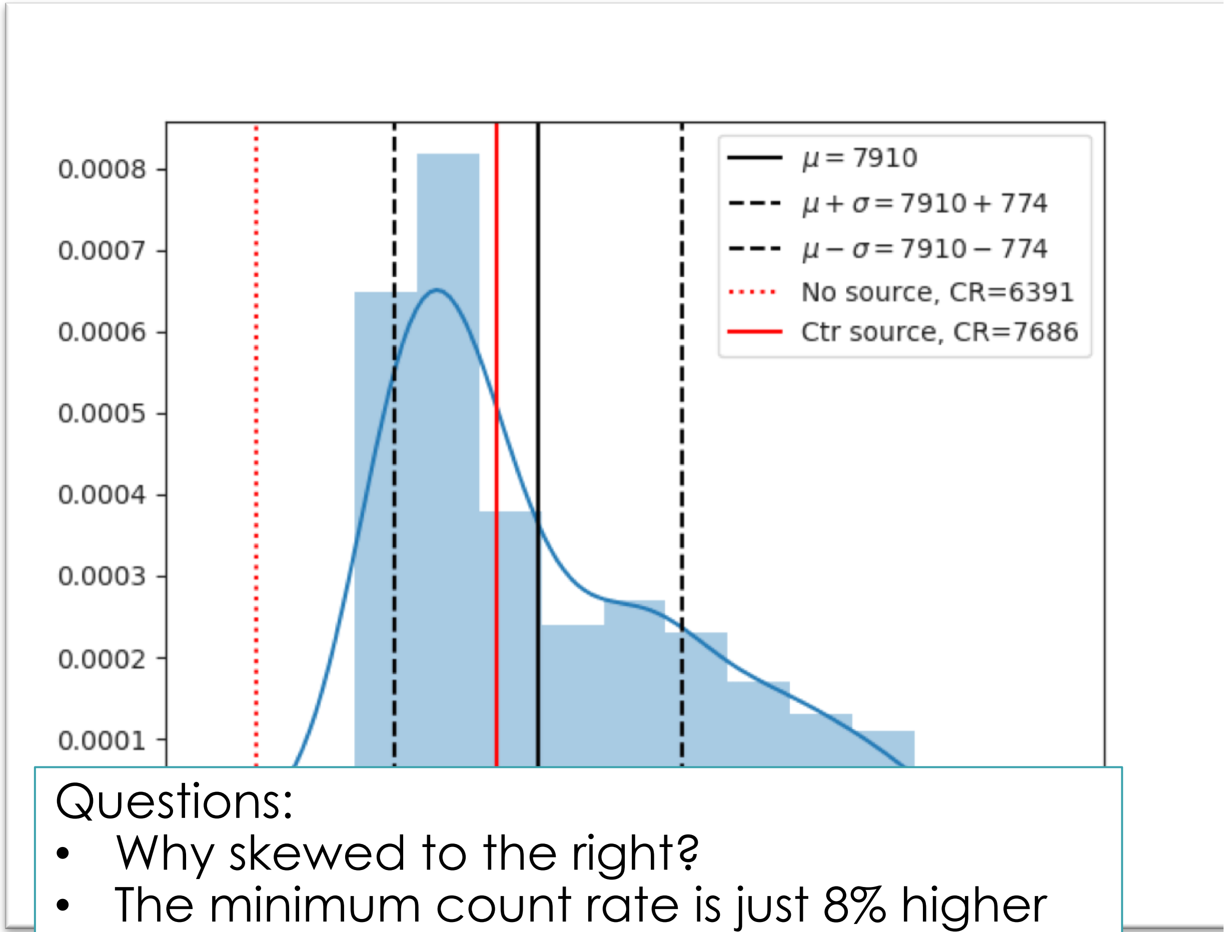
- Allow for the HEU source to be randomly oriented at the bottom of the barrel
  - Off-centered location
  - Allow rotated configuration
- Sampler model created to perturb geometry based on free rotation angle and random location at the bottom of the barrel
- Sampler Details:
  - 300 samples for "step 1" calculation
  - 300 samples for "step 2" calculation
  - 600 MAVRIC calculations total





Sampler Results

- Detector count rates
  - Only D-T source: 6391
  - **D-T source + LEU source** **% higher**
  - Nominal: 7686 20%
  - 300-sample min: 6922 8%
  - 300-sample median: 7614 19%
  - 300-sample mean: 7910 24%
  - 300-sample max: 9934 55%
- Distribution:
  - Skewed to the right
  - 300-sample SD is 774 (10% relative to mean)
  - Monte Carlo uncertainties < 1% for all samples

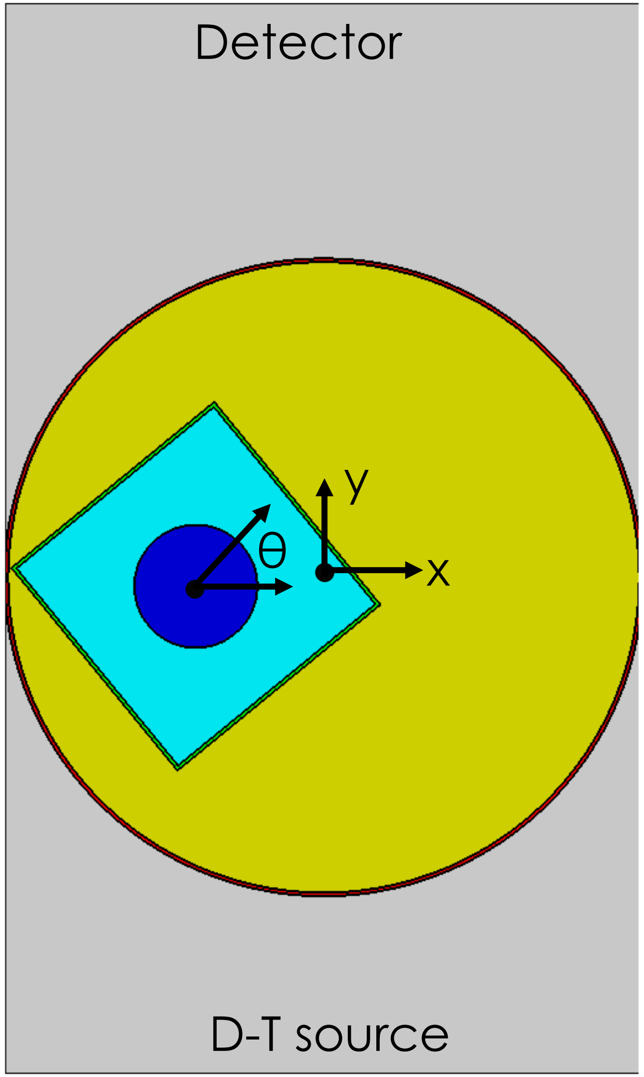


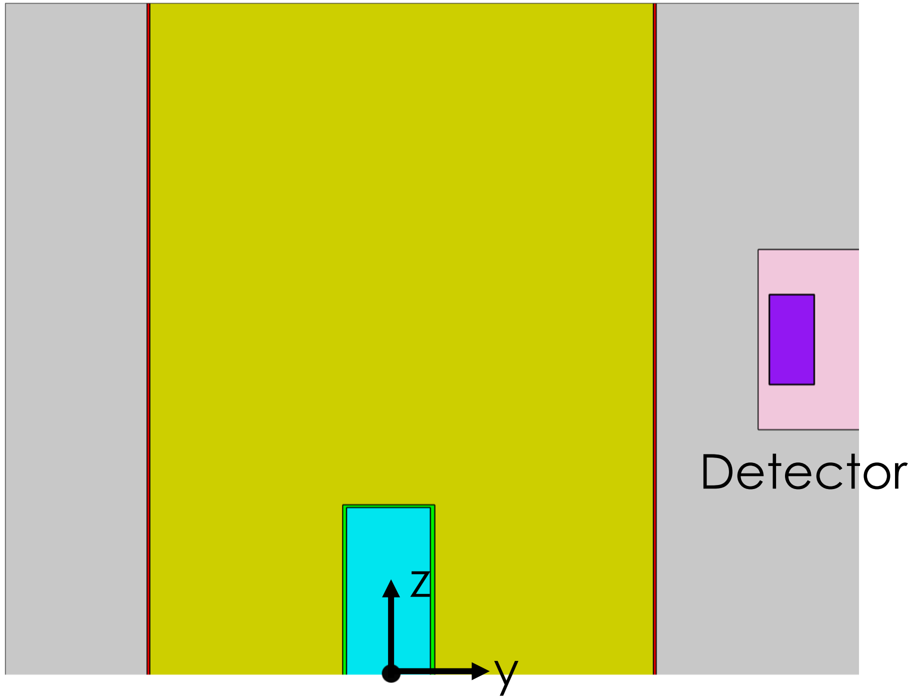
Questions:

- Why skewed to the right?
- The minimum count rate is just 8% higher than the count rate with only D-T source. Is this too small of a difference?

Correlation Analysis of 4 variables

1. count rate
   - Our quantity of interest
2. rotation angle
   - angle = 0: aligned with XY axis
   - angle = 45: see figure
3. x
   - x=0: Source is in direct path of D-T neutrons towards detector
4. y
   - y < 0: Source is closer to D-T source
   - y > 0: Source is closer to detector



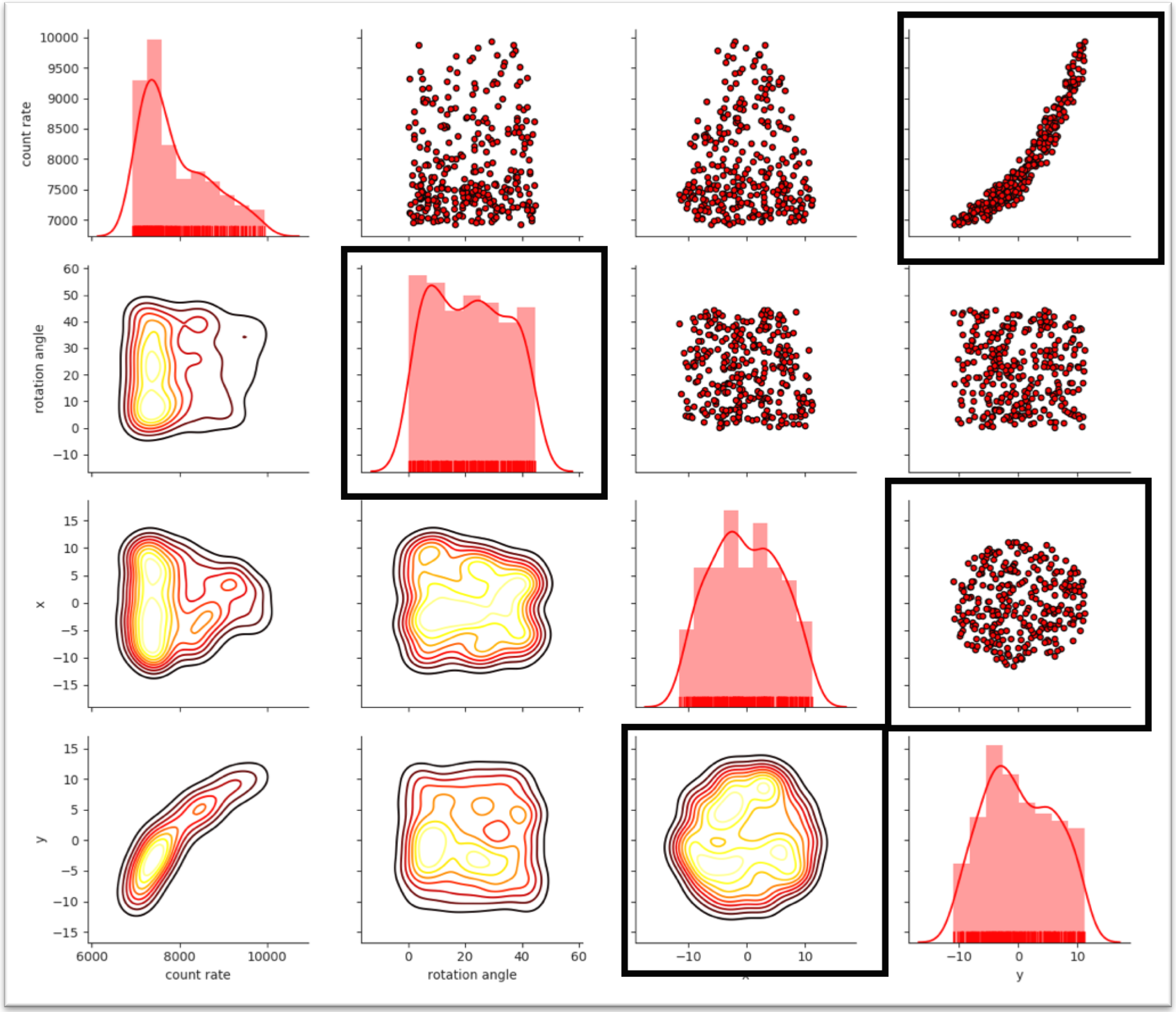


Correlation Analysis

Observations

- Visual Confirmation of "good" sampling
  - Angle Histogram
  - X,Y Scatter
- Strong correlation between count rate and y-distance

	CR	θ	x	y
CR	1			
θ	0.09	1		
x	0.02	-0.08	1	
y	0.95	-0.04	0.04	1



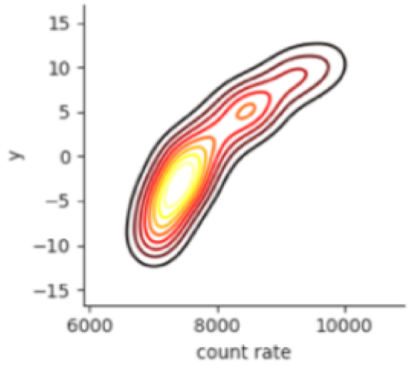
Python Seaborn PairGrid plot

Count Rate vs y distance

- Correlation coefficient is 0.95
- Count rate increases as y-distance increases
- Count rate increases if the HEU source is closer to detector
- Physics (assume x=0):
  - 14 MeV D-T neutrons leave source, travel towards HEU source
  - Some neutrons make it to the HEU source, induce fission
  - Some U-235 fission neutrons (~1-2 MeV) travel to detector, induce a count
  - Fission neutrons attenuate more than D-T neutrons
  - => Sources closer to detector induce higher count rate
- Physics (x≠0):
  - x displacement increases travel distance from D-T source to HEU source and HEU source to detector
  - Count rate decreases as travel distance (or attenuation) increases
  - x > 0 displacement is the same as x < 0 displacement due to problem symmetry

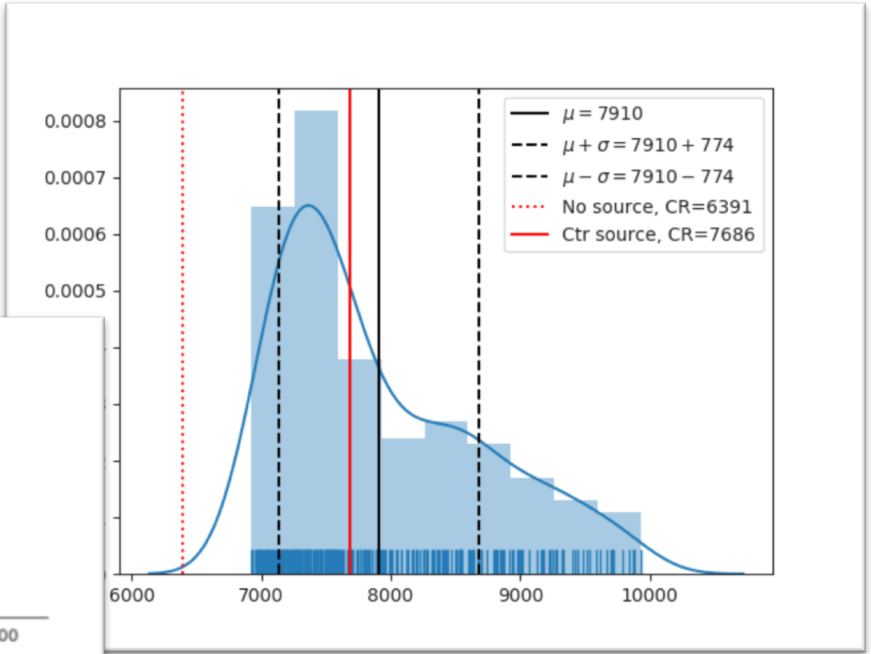
Correlation matrix

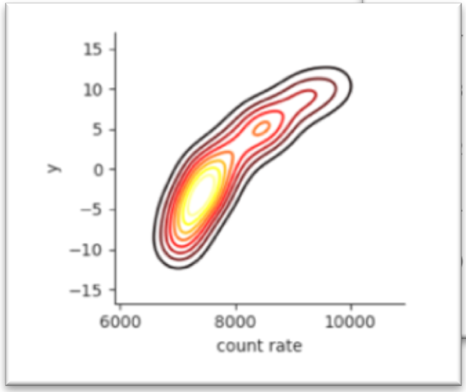
	CR	θ	x	y
CR	1			
θ	0.09	1		
x	0.02	-0.08	1	
y	0.95	-0.04	0.04	1



Why skewed to the right?

- Only a small subset of sampling lead to high count rates
  - y > 0
  - x close to zero
- All other samples lead to low count rates
  - Large |x|
  - Small y
- What about rotation angle?
  - Partial correlation coefficient matrix suggests count rate increases as angle increases
  - Physics:
    - Rotated configuration decreases water MFP from D-T source to HEU source and from HEU source to detector
    - Count rate increases as water absorption decreases
  - Need to perform additional parametric analysis to confirm





Partial Rank correlation matrix

	CR	θ	x	y
CR	1			
θ	0.39	1		
x	-0.01	-0.07	1	
y	0.95	-0.39	0.02	1

Conclusions

- The MAVRIC and Sampler sequences of SCALE have been used to perform uncertainty analysis for a neutron interrogation system
  - A strong correlation between count rate and distance from detector was observed.
    - SNM closer to the detector (and farther from the interrogation source) yields higher count rates because interrogation neutrons penetrate much farther than fission neutrons.
    - There is a slight correlation between box rotation angle and count rate because neutrons penetrate farther through balsa wood than through water. Smaller count rates lead to more ambiguity regarding the presence of source.
- Although all configurations led to count rates larger than the empty barrel count rate, differences can be as low as 8% - other sources of uncertainty (size, enrichment) will cause more ambiguity in source identification.