Sandia National Laboratories

Radioisotope Identification with List-Mode Gamma Ray Data

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Introduction

- List-mode data is comprised of energy-time pairs.
- Full gamma ray spectral analysis is the industry standard.
- Current analysis ignores the time domain, has long dwell times, and struggles with sources containing similarly-spaced spectral peaks.

Research Question:

Can the time domain be leveraged to aid in the identification of radioisotopes?

Datasets

- 3 datasets were created, all with a stationary detector and stationary sources
- Events within the first 100s to 1200s interval were used

Descriptions:

July 2022:

- Sources: Cs-137, Y-88, Ba-133, U-232, Ba-133+U-232

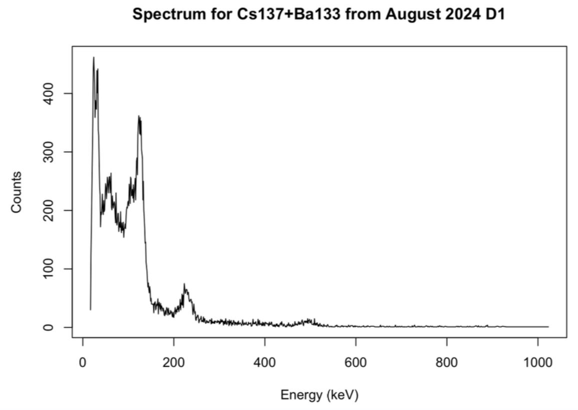
April 2024:

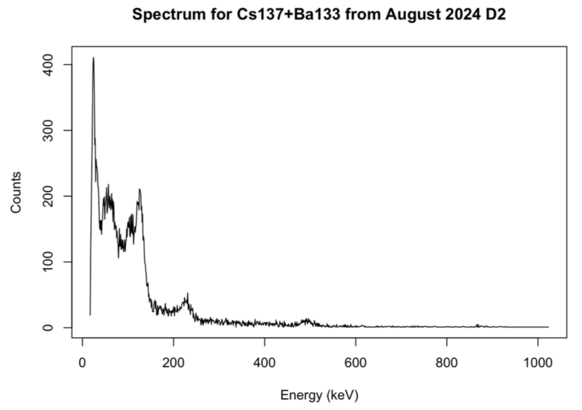
- Sources: Ba-133, U-232, Ba-133+U-232

August 2024:

- Sources: Cs-137, Y-88, Ba-133, Cs-137+Ba-133
- The gross count rate is roughly the same across sources.
- Two sets of distances were used

	Distance 1 (D1)		Distance 2 (D2)	
Source	Distance	Gross Count Rate	Distance	Gross Count Rate
Cs-137	10ft 2in	1598	15ft 2.5in	1181
Y-88	7ft 1.5in	1738	11ft 4in	1230
Ba-133	21ft 6in	1827	29ft	1381
Cs-137 & Ba-133	22ft 9in	1849	31ft	1350
Background		751		





Exploratory Data Analysis

Correlation metrics:

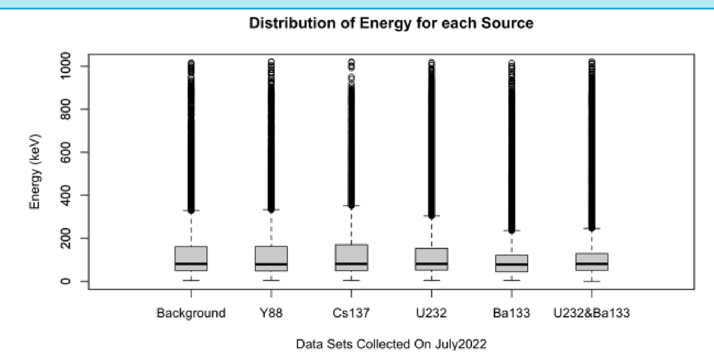
- Pearson Correlation: ✗
- Spearman's rho: ✗
- Autocorrelation: ✗
- Cross-Correlation: ✗
- ✗ = no correlation found

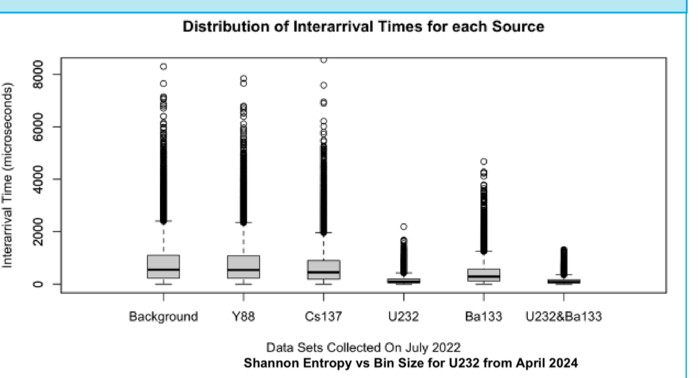
Box & Whisker Plots:

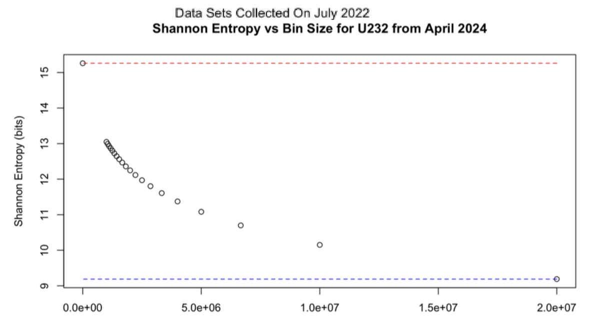
- Energy: Differences across sources
- Interarrival time: Differences across sources

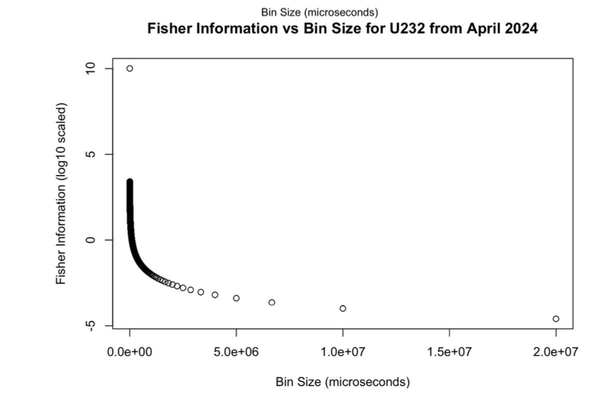
Information Metrics:

- Shannon Entropy: Decreases with increasing bin size
- Fisher Information: Decreases with increasing bin size









Probabilistic Classifier

- **First Model:**
  - Assume: Radioactive decay is a Poisson process
  - Assume: K isotopes + 1 background
  - Assume: unique rates of decay per isotope so that $\lambda_0 \neq \cdots \neq \lambda_k$
  - Assume: independence between time and energy
  - Assume: Mixture distribution of energies
  - Event counts$= \sum_{i=0}^{K} N_t^i \sim Poisson\left(\sum_{i=0}^{K} \lambda_i t\right)$
  - Interarrival times$\sim Exp\left(\sum_{k=0}^{K} \lambda_k\right)$
  - Energy$\rightarrow p_E(e) = \sum_{i=0}^{K} \pi_i p_{E_i}(e), p_{E_0}(e) = \sum_{b=1}^{B} p_b \frac{e^{-\alpha_b} \alpha_b^e}{e!}$
  - Histogram density approximator for $p_E(e)$ is $p_{E_i}^*$
  - Estimated probability density of source i: $\hat{p}_{E_i}(e) = \frac{p_{E_i}^*(e)}{\sum_{e \in \varepsilon} p_{E_i}^*(e)}$
  - Mixing proportions: $\hat{\boldsymbol{\pi}} = \underset{\boldsymbol{\pi}}{argmin} \left(\hat{p}_{E|K=k}(e) - \sum_{i=0}^{K} \pi_i \hat{p}_{E_i}(e)\right)^2$
  - Recursive MLEs of λ_k
  - Classification based on max log-likelihood of new sequence
- **Extended α Model:**
  - Designed to handle varying background effects ("SNR")
  - Maximum a posteriori estimate of α where $\lambda_i' = \alpha \lambda_i$

Classifier Analysis

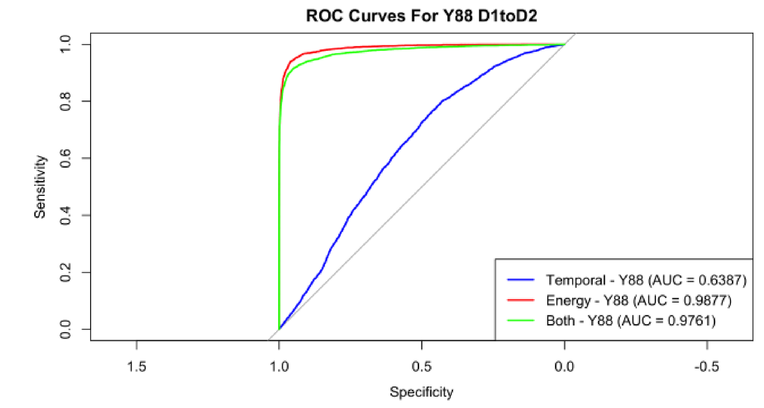
Accuracy:

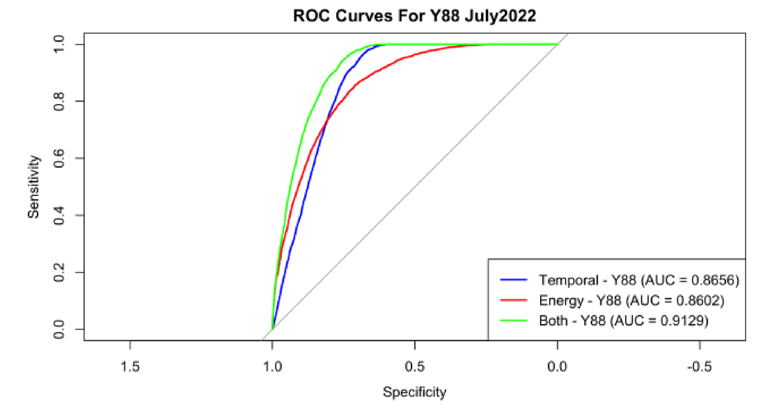
- Better together: Energy & Time Models
- Accounting for "SNR" is beneficial

Accuracy Results			
Experiment:	Time Model	Energy Model	Energy & Time Model
1: July 2022	0.7107	0.5498	0.6565
1-α: July 2022	0.7018	0.5498	0.6200
2: April 2024	0.8774	0.3890	0.6898
3: D1 to D1	0.4850	0.7368	0.8249
3-α: D1 to D1	0.3334	0.5436	0.8479
4: D1 to D2	0.1787	0.3864	0.5307
4-α: D1 to D2	0.3333	0.4782	0.7504
5: D2 to D1	0.2509	0.6636	0.7404
5-α: D2 to D1	0.3333	0.8799	0.9936
6: D2 to D2	0.5101	0.5476	0.7451
6-α: D2 to D2	0.3333	0.8372	0.9699
7: Mix to Mix	0.5037	0.6249	0.7488
7-α: Mix to Mix	0.3333	0.6442	0.9201

ROC Curves:

- Comparison shows problem with 1st Model
- Mostly better together





Multi-class AUC:

- Similar to ROC curves analysis

Multi-class AUC Results			
Experiment:	Time Model	Energy Model	Energy & Time Model
1: July 2022	0.9454	0.9105	0.9644
2: April 2024	0.9742	0.4845	0.9774
3: D1 to D1	0.7905	0.9614	0.9772
4: D1 to D2	0.5676	0.9171	0.9077
5: D2 to D1	0.5934	0.9167	0.9146
6: D2 to D2	0.8197	0.9313	0.9599
7: Mix to Mix	0.8049	0.9462	0.9662

McNemar's Test:

- P-value analysis suggests that Energy & Time Models are better than Energy Models

Conclusion

- Linear relationships not found
- May be meaningful differences across the distributions of interarrival times across radiological sources.
- Created a new probabilistic classifier that allowed for the comparison of models that used temporal information, energy information, or both combined
- Using Energy & Time information leads to better performing models
- Further investigations are warranted

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