Directional Localization of Gamma-Ray Sources Using a Compact Shielded CZT Detector Array and Gradient-Boosted Decision Trees

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Motivation and concept

Rapid localization of gamma-ray sources is important for nuclear security, border monitoring and radiological emergency response. Survey meters provide limited intrinsic directionality, while coded-aperture systems [1] and compron cameras are more complex.

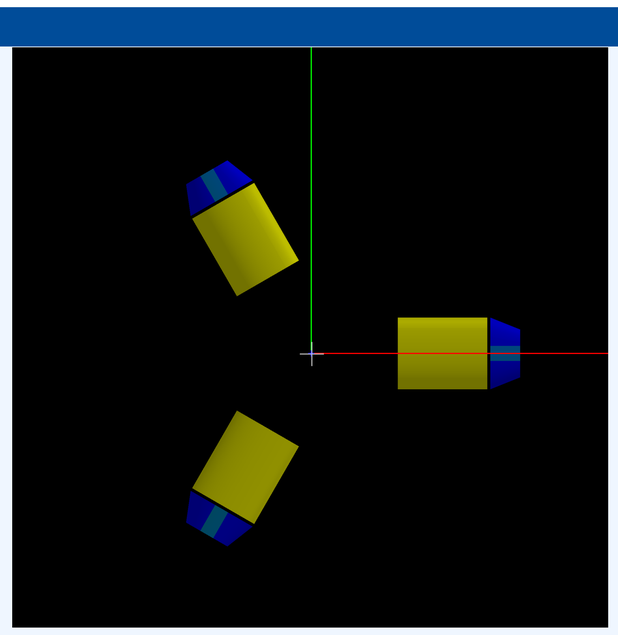
Objective

Investigate a compact, non-rotating directional detector that uses the count-rate asymmetry induced by passive shielding and a gradient-boosted decision tree (GBDT) to estimate source azimuth.

Detector architecture and GEANT4 simulation

- **Detector system:** three shielded CZT detector channels, each with a 0.5 cm^3 CZT crystal.
- **Geometry:** detectors arranged azimuthally at 120° around a common center.
- **Shielding:** asymmetric lead cone and cylindrical lead endcap create a direction-dependent response.
- **Source:** 1 mCi ^{137}Cs point source placed 50 m from the detector center.
- **Angular scan:** 0° to 355° in 5° steps.
- **Output per angle:** total counts in each detector channel over a fixed acquisition interval.

Detector Model



The proposed directional detection system consists of three compact shielded detector channels arranged azimuthally at 120° intervals around a common center. Each detector is surrounded by an asymmetric lead shielding structure, which modifies its count-rate response as a function of the incident source direction. As the radioactive source rotates around the array, the three detectors produce distinct but complementary angular-response curves. The detector system has been simulated using GEANT4 [2]. The relative count pattern among the three channels provides the directional information used by the Gradient-Boosted Decision Tree model to estimate the source azimuth without requiring mechanical rotation or image reconstruction.

Single-detector angular modulation

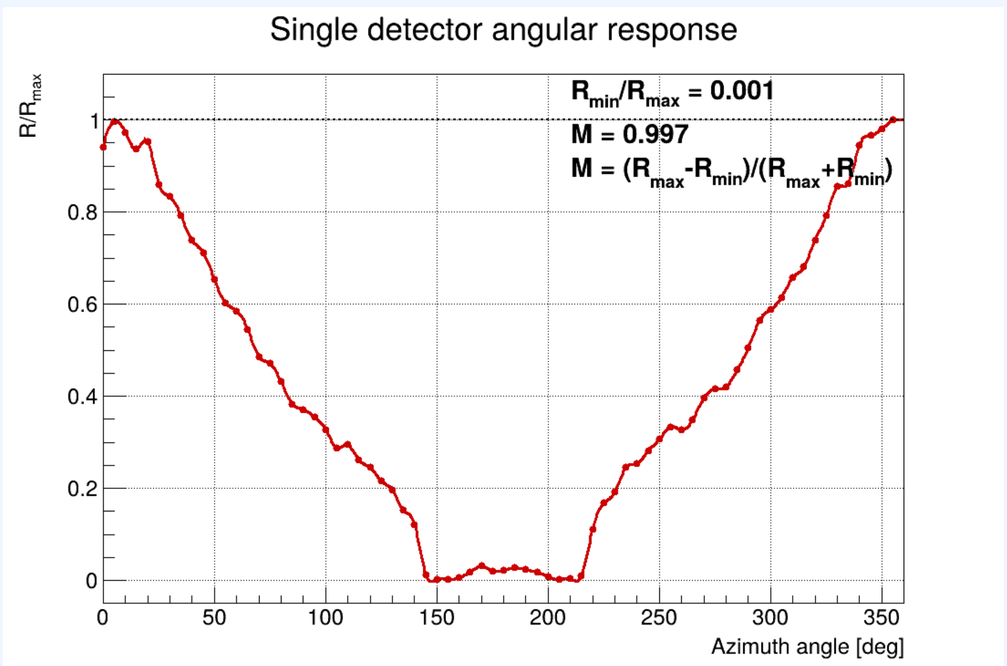
One shielded detector channel was first examined to verify that the shield converts source direction into measurable count-rate modulation. The response was normalized to its maximum value:

$$R_{\mathrm{norm}}(\theta) = \frac{R(\theta)}{R_{\mathrm{max}}}.$$

Two scalar indicators summarize the directional contrast:

$$\frac{R_{\mathrm{min}}}{R_{\mathrm{max}}} = 0.001, \qquad M = \frac{R_{\mathrm{max}} - R_{\mathrm{min}}}{R_{\mathrm{max}} + R_{\mathrm{min}}} = 0.997.$$

A very small $R_{\mathrm{min}}/R_{\mathrm{max}}$ and a modulation factor close to unity show strong suppression in shielded directions. These values demonstrate channel directionality; unique 360° localization requires combining the three shifted detector responses.



Normalized angular response of detector 1. The deep minimum and high modulation factor quantify shielding-induced angular contrast.

Feature construction and Poisson sampling

Repeated pseudo-acquisitions were generated by treating the expected detector counts as Poisson means. This models counting-statistics fluctuations while preserving the GEANT4 angular pattern.

For detector counts N_1, N_2 and N_3, normalized fractions were calculated as

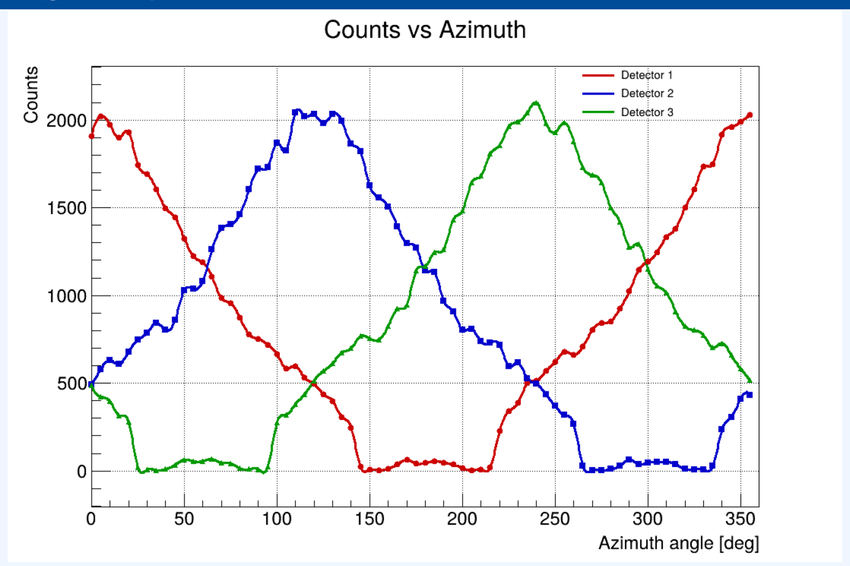
$$p_i = \frac{N_i}{N_1 + N_2 + N_3}, \quad i = 1, 2, 3.$$

The final GBDT input vector was

$$\mathbf{x} = [p_1,\ p_2,\ p_3,\ p_1/p_2,\ p_1/p_3,\ p_2/p_3].$$

The pairwise ratios increase sensitivity to the relative angular pattern and reduce dependence on absolute source strength.

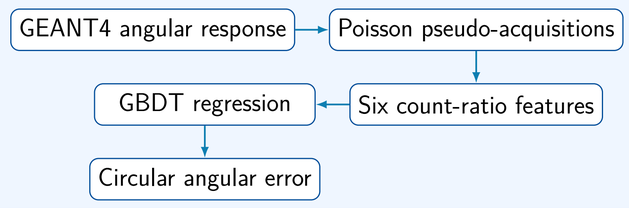
Three-detector angular response



The three shielded detector channels exhibit distinct angular-response curves because each detector is oriented at a different azimuthal position within the array. As the source direction changes, the count rate increases in the detector facing the source and decreases in the more shielded channels. The shifted maxima and minima of the three curves therefore form a direction-dependent response vector, which is used by the Gradient-Boosted Decision Tree model to infer the source azimuth.

Machine-learning localization model

A gradient-boosted decision tree model with 100 trees was trained using KNIME [3] to map the six count-ratio features to source azimuth. GBDT is well suited to this small tabular feature set and remains computationally lightweight for field deployment.

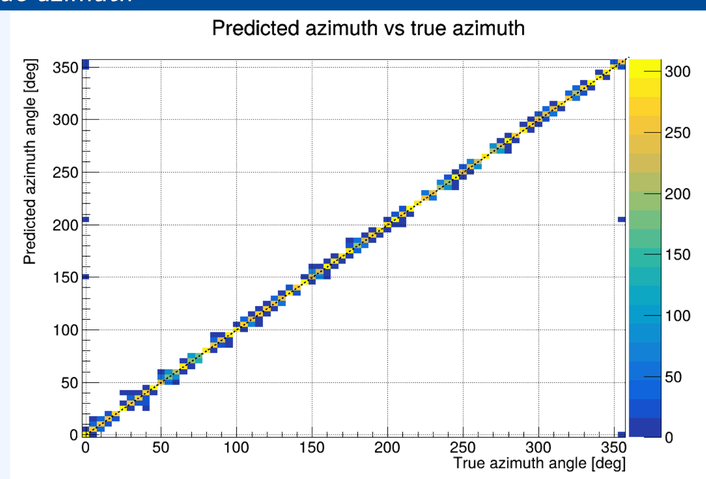


Key performance indicators

$R_{\mathrm{min}}/R_{\mathrm{max}}$	M	$\sim 2°$
0.001	0.997	angular accuracy
single detector	modulation factor	GBDT localization

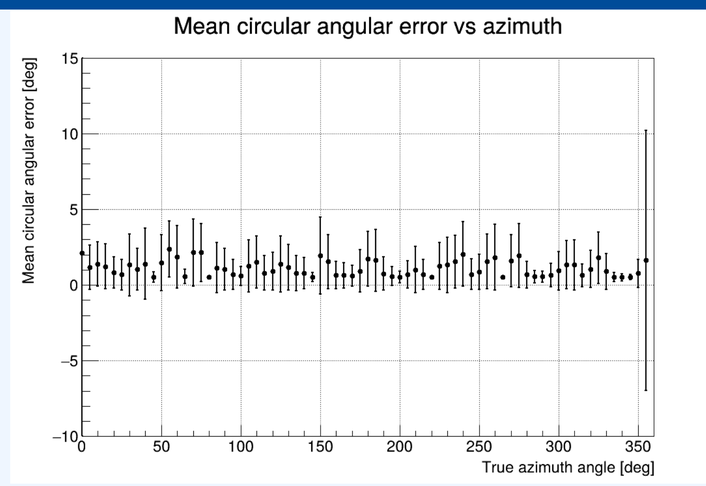
These indicators summarize shielding contrast and final localization performance.

Predicted versus true azimuth



The two-dimensional distribution of predicted azimuth versus true azimuth shows a strong diagonal structure, indicating that the GBDT model accurately reproduces the simulated source direction over most of the angular range. Events concentrated along the diagonal correspond to correct localization, while the small deviations from the ideal line reflect the residual uncertainty introduced by counting statistics and the finite angular response of the detector array.

Circular angular error



The mean circular angular error is approximately 1° over most of the azimuthal range, demonstrating accurate and stable directional performance of the GBDT model. The error bars represent the standard deviation obtained from repeated Poisson-sampled realizations at each source angle and therefore quantify the effect of counting statistics on the predicted direction. The small mean error and the absence of large systematic angular trends indicate that the detector-response features provide sufficient information for reliable source localization.

Conclusions

- Lead cone and endcap produce a highly anisotropic response.
- Three channels separated by 120° provide complementary angular information.
- Six scalar features support accurate azimuth estimation with lightweight GBDT.
- Compact, non-rotating concept suitable for fixed-site and mobile radiological search.

QR code and references

Selected references

1. K. Karafasoulis et al."A machine learning approach in the estimation of a radioactive source position using a coded aperture device,", JINST 18 (2023) C01062.
2. S. Agostinelli et al., GEANT4, Nucl. Instrum. Meth. A 506 (2003) 250–303.
3. M.R. Berthold,et al , "KNIME: The Konstanz Information Miner," Studies in Classification, Data Analysis, and Knowledge Organization, Springer (2007)