Coded Cube Camera for Gamma-ray (C3G)

Development and Experimental Evaluation of a Cost-Effective Compact 4π Gamma-Ray Imager

Yoshiharu Kitayama*[1], Keitaro Hitomi[2], Mitsuhiro Nogami[2], Yong-Gen Yin[3], Kazuyuki Enomoto[3], Naoto Yamada[3], Yusaku Noda[3], Hiromi Nakai[1], Naoki Kawachi[1, 3]

1. Fukushima Institute for Research, Education and Innovation (F-REI) 2. Tohoku University 3.National Institutes for Quantum Science and Technology (QST)

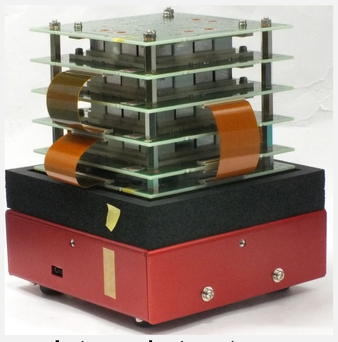
Introduction

Conventional 4π gamma-ray imagers are often expensive because they rely on many detector channels and complex event-by-event signal processing. To reduce this complexity, we developed the **Coded Cube Camera for Gamma-ray (C3G)**, which estimates gamma-ray source distributions from detector response patterns produced by a three-dimensional arrangement of scintillators and lead shielding cubes.

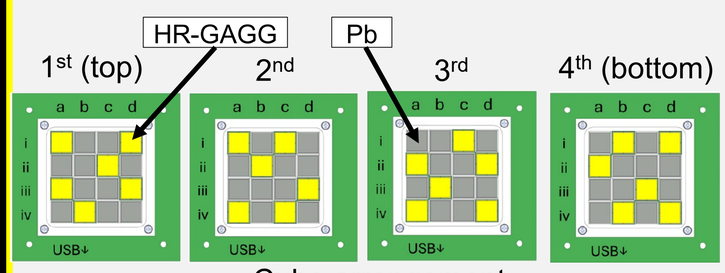
This work presents the **first experimental evaluation of a 4 × 4 × 4, 24-detector C3G** system, developed as an extension of our previous 3 × 3 × 3 C3G studies [1,2]. The system uses only total count information, without coincidence detection or high-speed event-by-event processing and was experimentally evaluated using ^{11}C sources to demonstrate the feasibility of compact and cost-effective 4π gamma-ray imaging.

1. Concept of C3G

External view



Internal structure



Cube arrangement

Cost-effective design

C3G estimates source distributions from **direction-dependent detector response patterns** generated by a 3D arrangement of scintillator and Pb cubes. The system consists of **only 24 HR-GAGG scintillators** and 40 Pb cubes in a compact 4 × 4 × 4 lattice. A single cube-board pattern is reused in four layers with 90° rotations, reducing the number of board designs and fabrication complexity. **This simple architecture enables cost-effective 4π imaging** while maintaining directional response over the full 4π field of view.

2. Image Reconstruction Algorithm

Model

$$\underbrace{\begin{pmatrix} y_1 \\ \vdots \\ y_{24} \end{pmatrix}}_{\boldsymbol{y}} \quad \text{Compare} \quad \underbrace{\begin{pmatrix} \hat{y}_1 \\ \vdots \\ \hat{y}_{24} \end{pmatrix}}_{\hat{\boldsymbol{y}}} = \underbrace{\begin{bmatrix} h_{1,1} & \cdots & h_{1,N} \\ \vdots & \ddots & \vdots \\ h_{24,1} & \cdots & h_{24,N} \end{bmatrix}}_{\boldsymbol{H}} \underbrace{\begin{pmatrix} x_1 \\ \vdots \\ x_N \end{pmatrix}}_{\boldsymbol{x}}$$

- $\boldsymbol{x}$: gamma-ray source distribution to be estimated
- $\boldsymbol{y}$: measured response pattern of the 24 detectors
- $\hat{\boldsymbol{y}}$: response pattern predicted from $\boldsymbol{x}$
- $\boldsymbol{H}$: response-function matrix

Equations

Predicted response

$$\hat{\boldsymbol{y}} = \boldsymbol{H}\boldsymbol{x}$$

Objective function

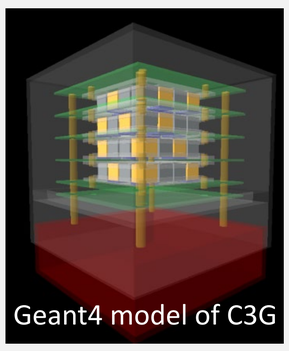
$$L(\boldsymbol{x}) = \|\boldsymbol{H}\boldsymbol{x} - \boldsymbol{y}\|^2$$

Basic gradient-descent update

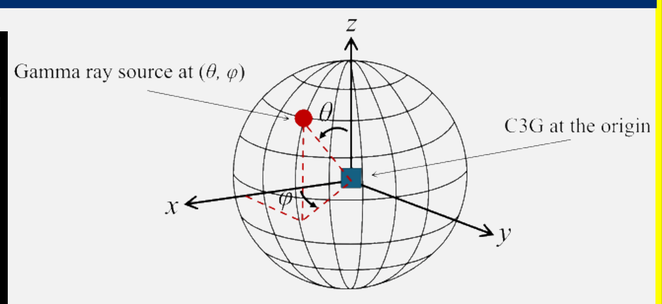
$$\boldsymbol{x}^{\text{new}} = \boldsymbol{x} - \varepsilon \nabla L(\boldsymbol{x})$$

The objective function was minimized using the **Adam optimizer** implemented in **TensorFlow**. A non-negativity constraint was imposed on the source distribution during each iteration.

3. Response Matrix Calculation



Geant4 model of C3G

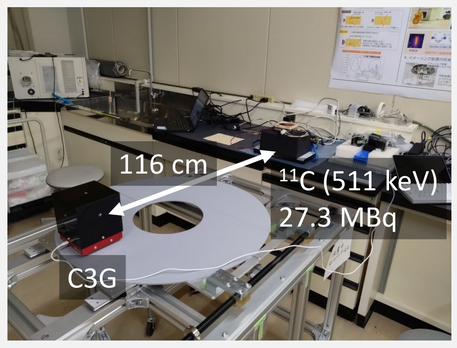


Coordinate system and irradiation geometry in the Geant4 simulation.

The response matrix $\boldsymbol{H}$ was calculated by **Geant4** simulation. 511 keV gamma rays were **irradiated from 614 directions** on a 10° mesh in azimuth angle φ and polar angle ϑ. The responses were **interpolated to a 5° mesh**, yielding **a response matrix for 2522 directions**.

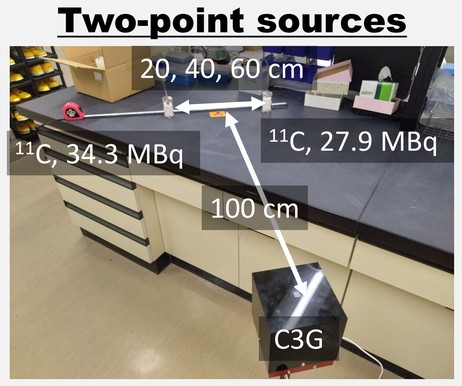
4. Experimental Setup

EXP 1: Single-point source



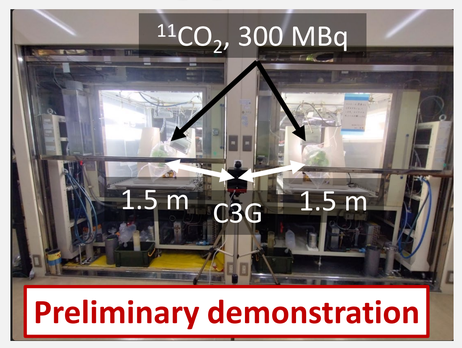
- Long-duration measurement
- Source **localization and decay tracking**

EXP 2: Two-point sources



- **Source separation test**
- 60, 40, and 20 cm separations at 100 cm from C3G

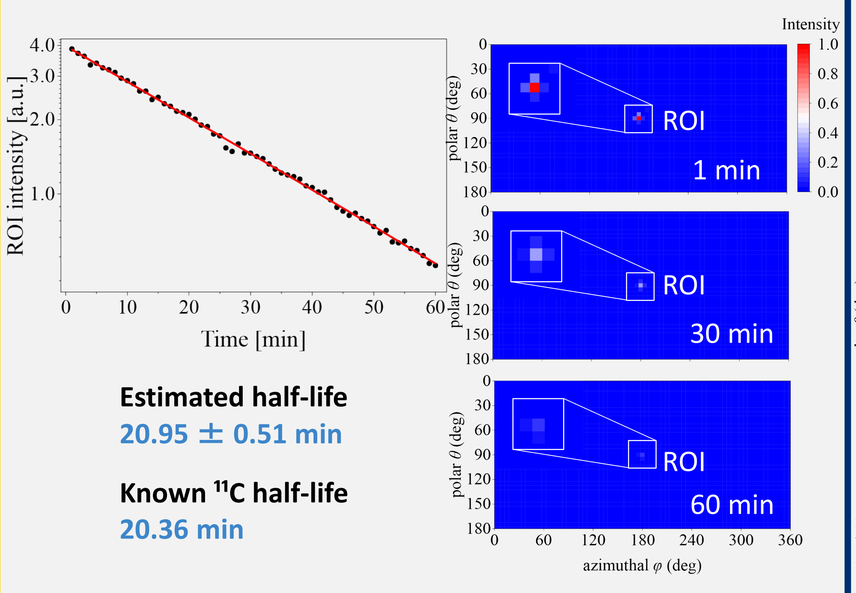
EXP 3: Moving gas source



- **Dynamic visualization** of a $^{11}CO_2$ gas source.
- **1 s measurement frames** overlaid on 4K video

5. Results

EXP 1: Single-point source

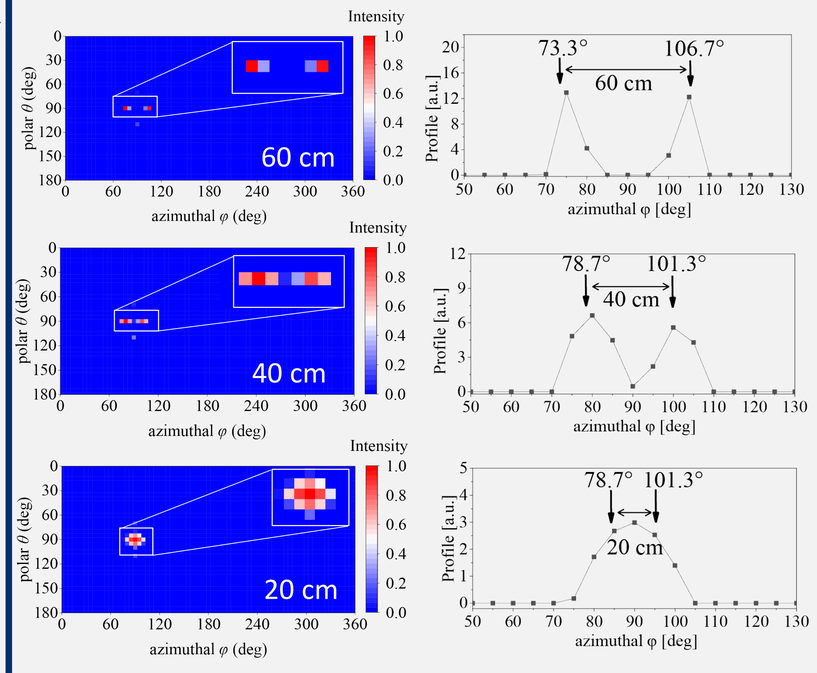


Estimated half-life
20.95 ± 0.51 min

Known ^{11}C half-life
20.36 min

The ^{11}C point source was correctly localized throughout the 60 min measurement. **The reconstructed intensity in the ROI decreased exponentially**, and the estimated half-life was 20.95 ± 0.51 min, in good agreement with the known half-life of ^{11}C, 20.36 min. This result shows that **C3G can track both source direction and temporal changes in radioactivity.**

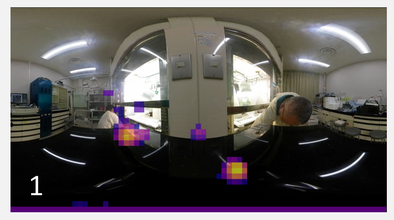
EXP 2: Two-point sources



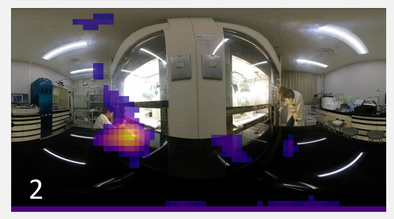
Two-source imaging was performed with source separations of 60, 40, and 20 cm at a source-to-C3G distance of 100 cm. **The two sources were clearly resolved at 60 and 40 cm**, whereas they were not clearly resolved at 20 cm. The minimum resolvable **angular separation under this condition was approximately 23°**

EXP 3: Moving gas source

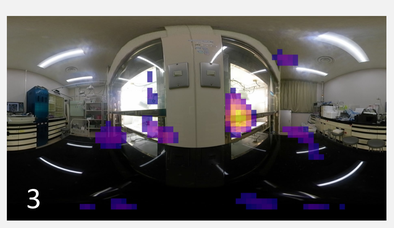
Preliminary demonstration



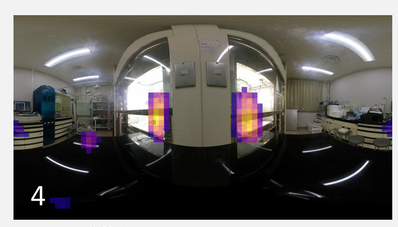
$t = 0$ s
Thawing of dry-ice-like $^{11}CO_2$



$t = 4$ s
Setting the thawed $^{11}CO_2$ gas source



$t = 86$ s
Gas entering the right chamber



$t = 131$ s
Gas entering the left chamber

As a preliminary demonstration, a **moving $^{11}CO_2$ gas** source was continuously imaged and overlaid on 4K video frames. The images were reconstructed using non-optimized parameters and are shown here as a **feasibility demonstration of dynamic 4π imaging**.

Conclusion

- A **compact 24-detector C3G** was developed.
- ^{11}C experiments confirmed **source localization, decay tracking, and two-source separation**.
- Preliminary dynamic imaging suggests potential for **wide-field** radiation monitoring.
- These results support compact, **cost-effective 4π gamma-ray imaging**.

References
[1] Y. Kitayama, M. Nogami, and K. Hitomi, “Simulation of a gamma-ray imaging technique using detector response patterns,” Jpn. J. Appl. Phys. 63, 032005 (2024).
[2] Y. Kitayama, M. Nogami, and K. Hitomi, “An experimental feasibility study of a 4π gamma-ray imager using detector response patterns,” Jpn. J. Appl. Phys. 63, 076502 (2024).