Implementation and verification of a free-moving 3D Compton imaging system for γ source term monitoring in Nuclear Power Plants

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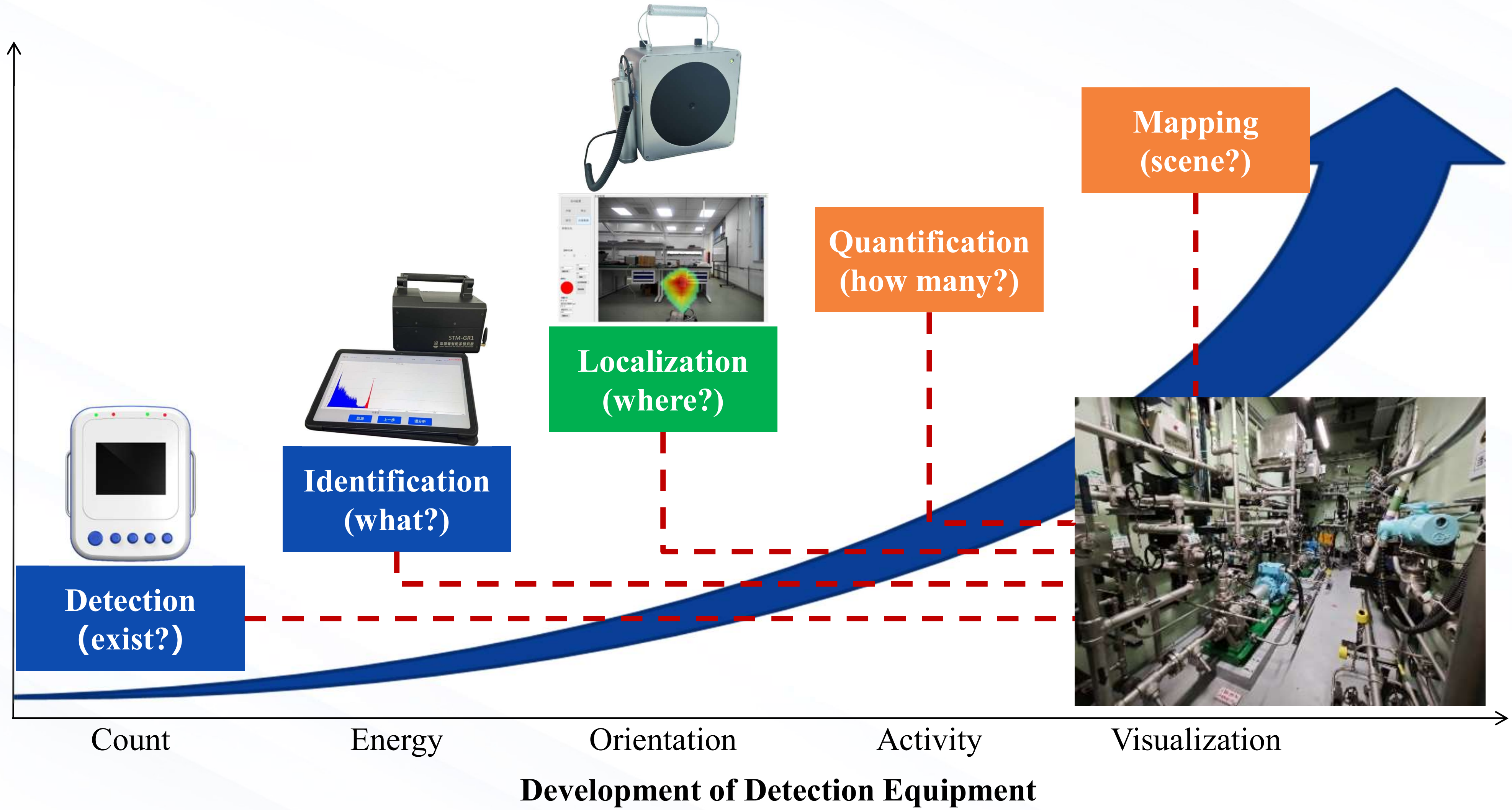
1. Why we develop 3D radiation imaging?



2. How to achieve 3D radiation imaging?

It is feasible to reconstruct 3D images by combining images from multiple perspectives. But, there are drawbacks:

- **Low efficiency**

the imaging system conducts static measurements at each perspective.

- **Low precision**

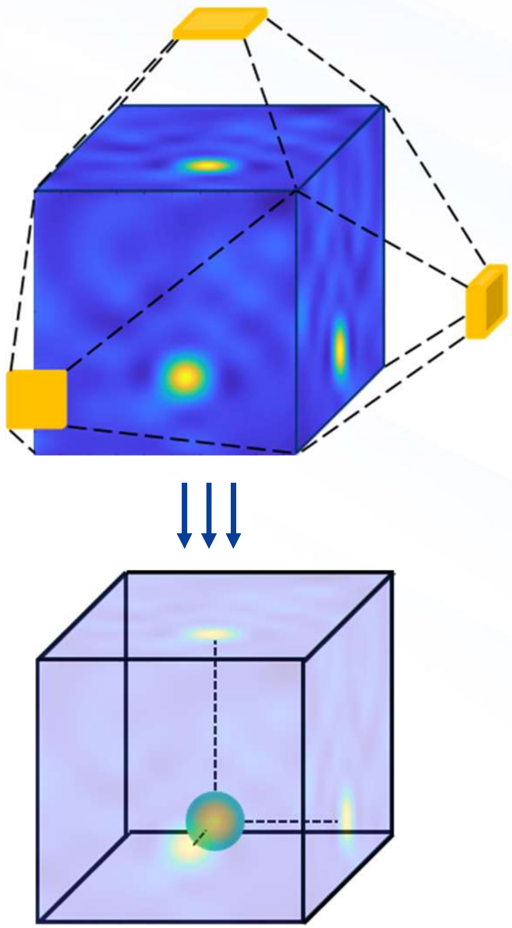
positioning and resolution uncertainty accumulates repeatedly during the calculation.

- **Low applicability**

space and time are not enough for measurements from all perspectives in most scenarios.

- **Low correlation with the scene**

no effective fusion with scene information.



2. How to achieve 3D radiation imaging?

Design of Free-moving Radiation Imaging

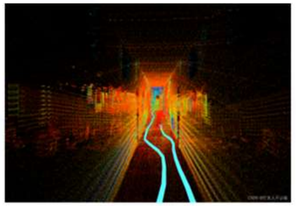
SLAM (Simultaneous localization and mapping):

locates the detector in real time and maps the three-dimensional model of scene.

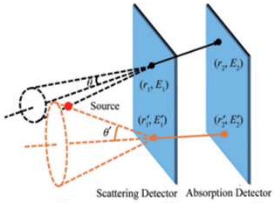
Compton imaging:

measures and calculates the direction of gamma rays one by one.

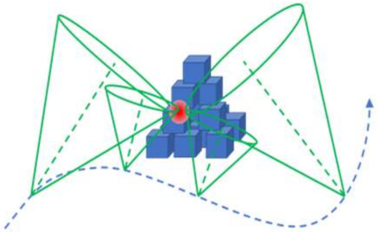
The direction of each gamma ray in three-dimensional space.



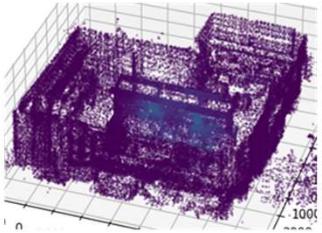
SLAM: path and scene



Compton Camera: list-mode γ-ray



Compton data in space



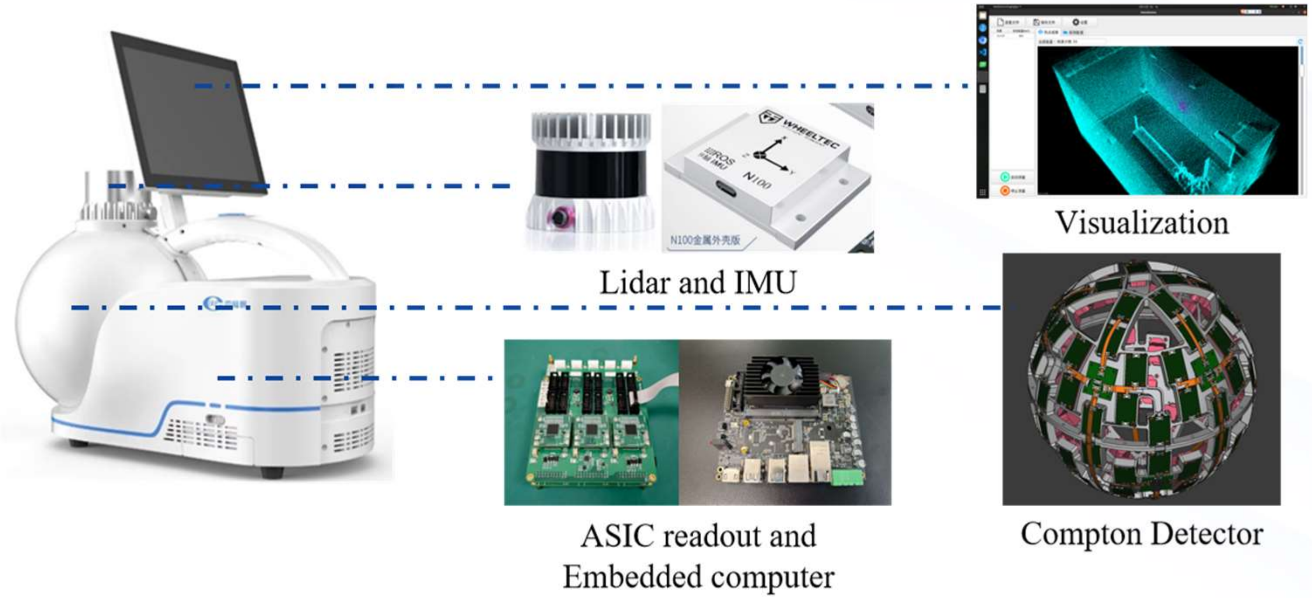
3D γ source distribution image

- **High efficiency movement measurement**
- **High-precision with scene constraints**
- **Strong visualization integrating scene models**

3. Portable 3D Compton imaging system

Portable 3D Compton imaging system consists of:

- Lidar and IMU for scene perception
- Spherical Detector composed of 80 GAGG:Ce crystals measures Compton data with consistent angle responses
- ASIC reads out the detector signal
- Embedded computer performs calculations for SLAM and imaging algorithms
- Touch screen for operation and visualization



4. 3D Imaging Algorithm

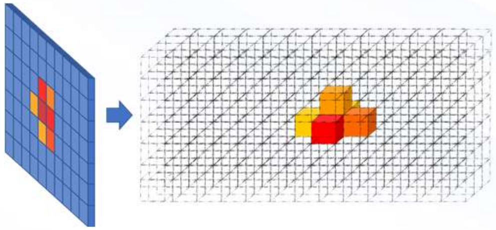
Algorithm based on ML-EM (Maximum Likelihood-Expectation Maximization)

Iterative formula of ML-EM :

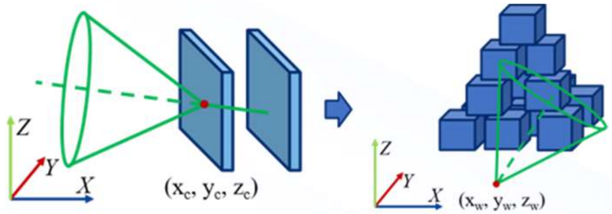
$$\lambda_j^{(l+1)} = \frac{\lambda_j^{(l)}}{s_j} \sum_{i=1}^{N} \frac{t_{ij}}{\sum_{k=1}^{M} t_{ik} \lambda_k^{(l)}}$$

i : serial number of γ-ray event
j : serial number of image pixel/voxel
λ_j : image intensity
t_{ij} : The probability that a photon from j is detected with the parameters (energy and location) of event i

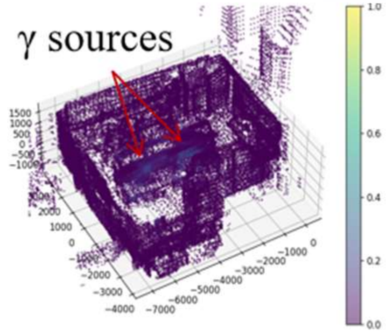
1. Change pixel j to voxel j



2. Convert Camera coordinate system to Scene coordinate system



Simulated imaging results:



4. 3D Imaging Algorithm

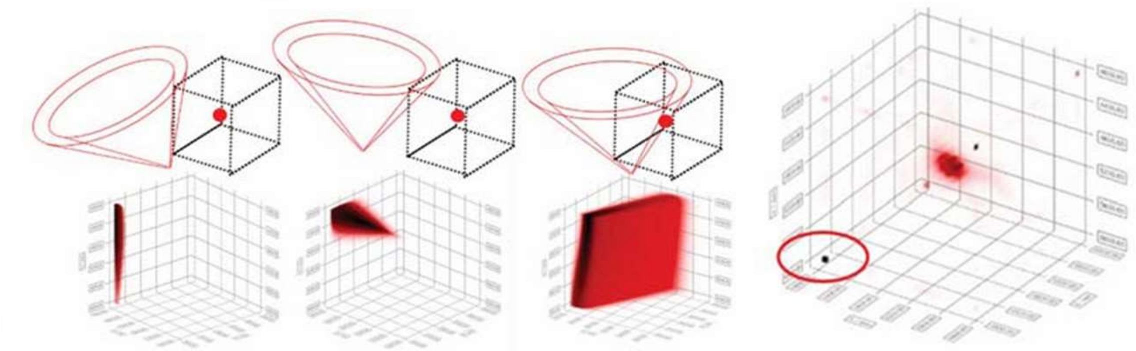
Algorithm based on ML-EM (Maximum Likelihood-Expectation Maximization)

$$\lambda_j^{(l+1)} = \frac{\lambda_j^{(l)}}{s_j} \sum_{i=1}^{N} \frac{t_{ij}}{\sum_{k=1}^{M} t_{ik} \lambda_k^{(l)}}$$

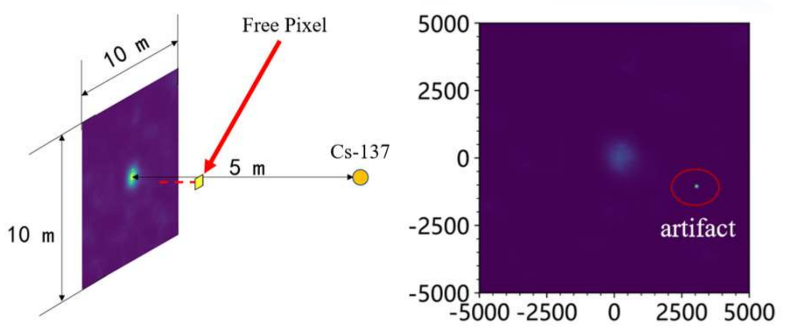
For some events, the Compton cones are not fully contained within the imaging space,

$\sum_{k=1}^{M} t_{ik} \lambda_k^{(l)}$ can vary by thousands of times, when t_{ij} approximately the same.

The importance of some events is greatly magnified, leading to artifacts at the edges



The principle of artifact generation



Reproduce artifacts through simulation

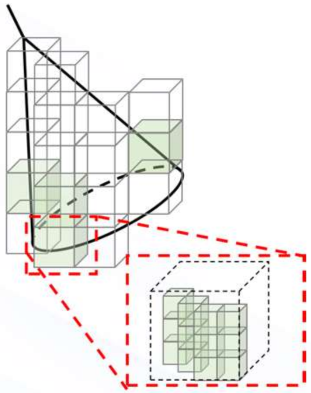
4. 3D Imaging Algorithm

SD-OE-RR (subset-driven origin ensemble algorithm with resolution recovery) Algorithm

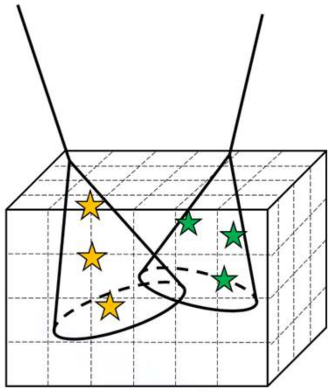
1.Calculate the probability distribution of voxels that intersect with the Compton cone

2. Select N voxels as the γ-ray origin randomly based on the probability distribution, get the initial image

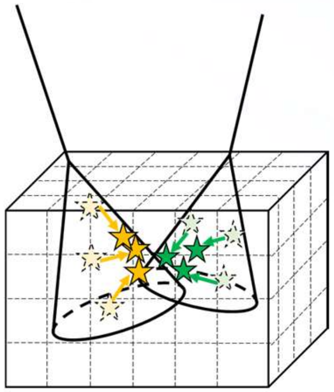
3. In each iteration, reselect these voxels randomly. If the new voxels make the γ-ray origin more concentrated, recerive the new voxels and update image



① calculate the probability distribution



② select N γ-ray origin pixels



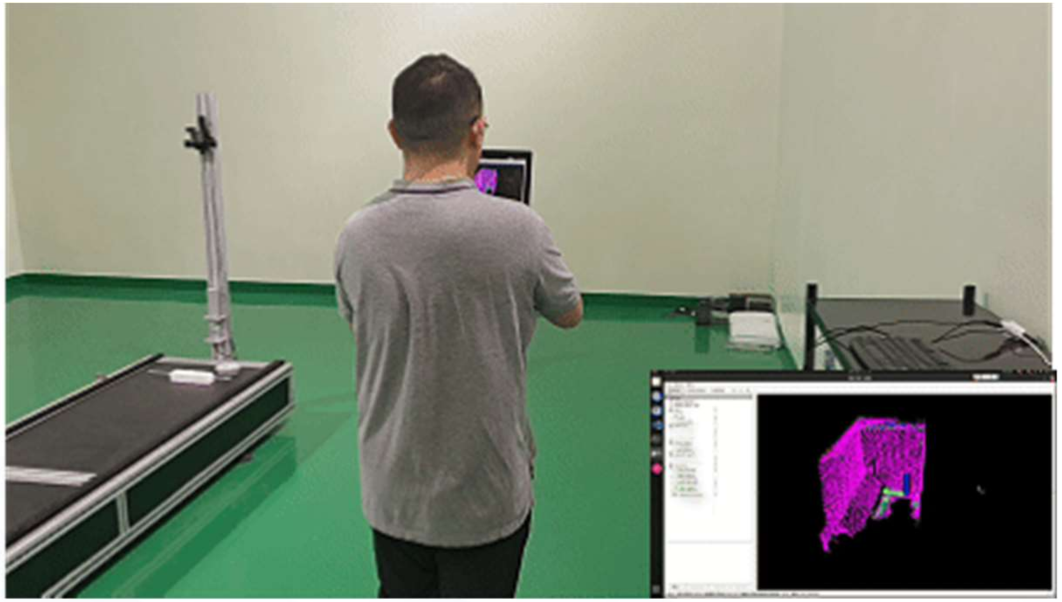
③ reselect pixels and update

5. Laboratory Experiment

Experiment Setup:

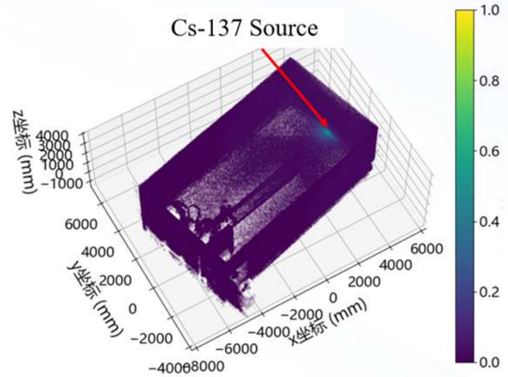
765.9μCi (2.8×10^7Bq) Cs-137 source

in **~100m²** laboratory



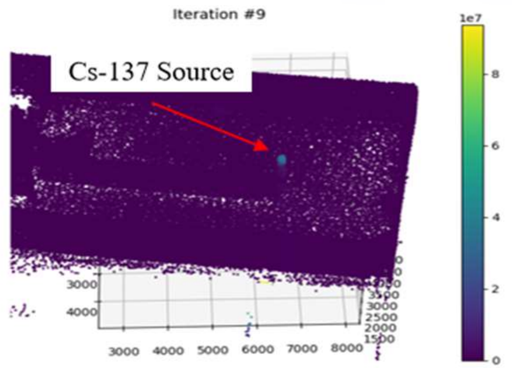
Experiment process

3D Imaging results:



The source is attached to the wall

(took 108 seconds, spatial resolution ~50cm)

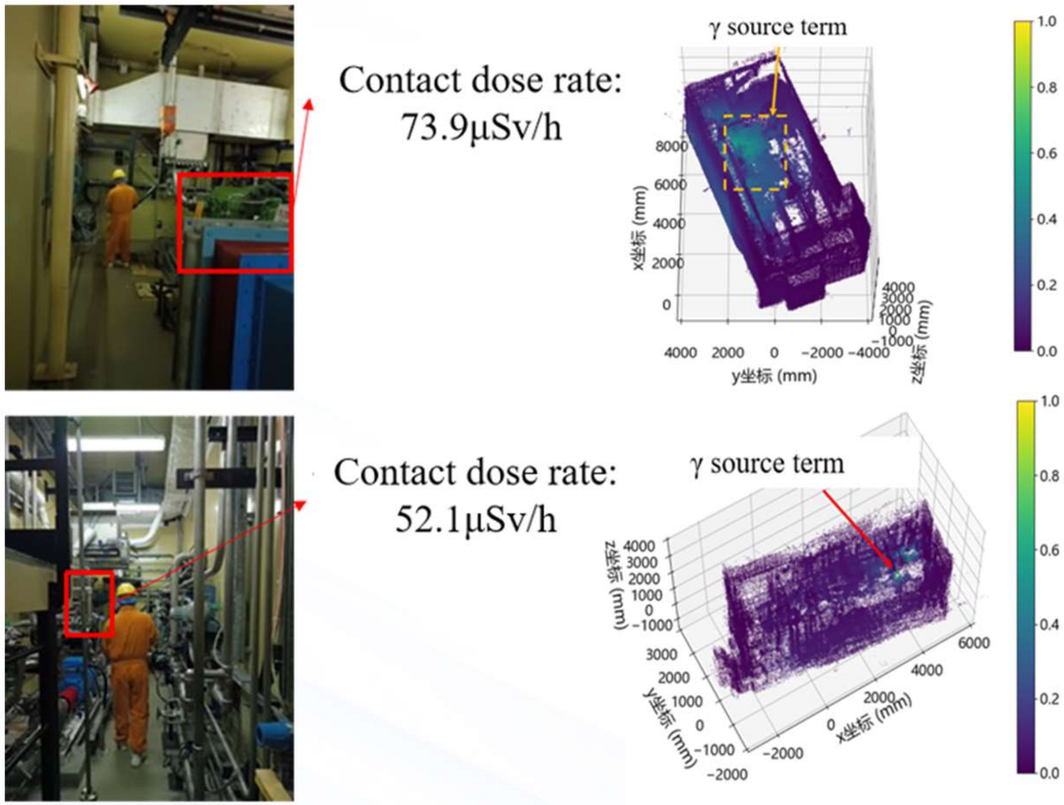


The source is placed on the middle pole

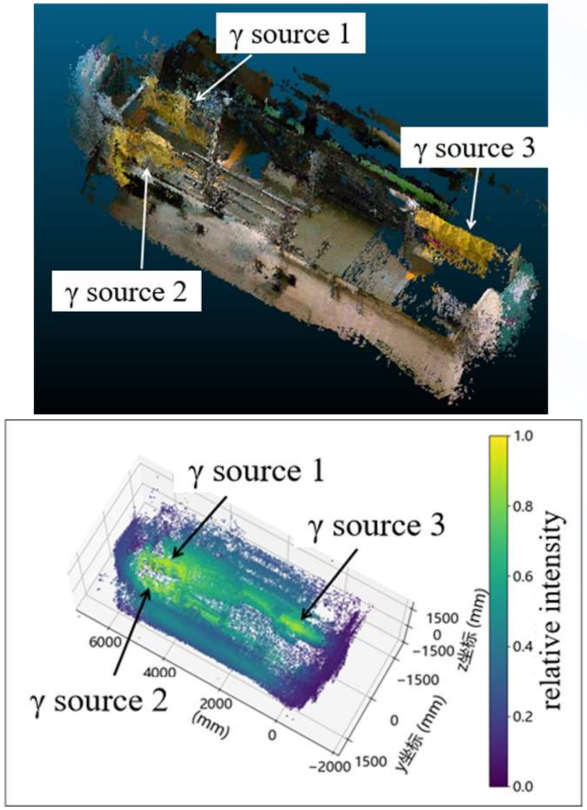
(took 61 seconds, spatial resolution ~10cm)

6. Application in NPP

Application and verification in the auxiliary plant of Qinshan Nuclear Power Plant.



Imaging results in the rooms with a single γ source



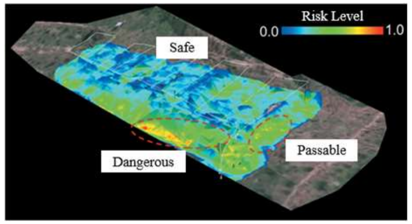
Imaging result in the room with multiple γ sources

7. Summary and Prospect

We have integrated SLAM with Compton cameras to develop a portable 3D Compton imaging system, which has achieved three-dimensional imaging of γ source terms in both laboratories and nuclear power plants.

Potential applications:

- Nuclear emergency and environmental monitoring



- Waste and decontamination

- Data acquisition of digital RP system

Drawbacks:

- Spatial resolution is not good enough
- Relative intensity need be corrected
- Compton imaging is not suitable for low-energy γ-rays

Thanks for Listening