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Indoor 3D Gamma Radiation Mapping Based on VSLAM and Its Preliminary Application in NPPs

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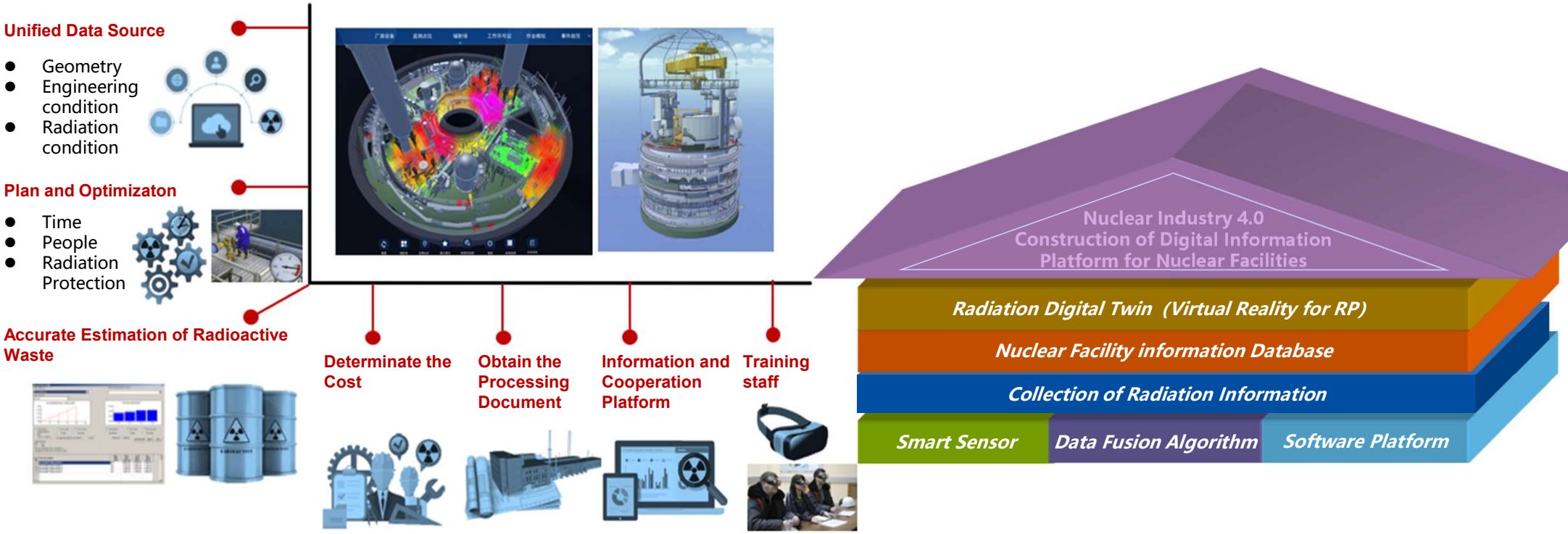
Background and Motivation

- **Nuclear facilities require fast, accurate radiation mapping**
- **Traditional methods: slow, labor-intensive, less adaptable**
- **Need for real-time, digital-compatible solutions**



Research Objective

- **Develop a rapid, accurate 3D gamma dose measurement method**
- **Utilize VSLAM for spatial mapping and dose integration**
- **Enhance efficiency, localization, and digital compatibility**

Traditional Mode

First measure distance

Then measure radiation

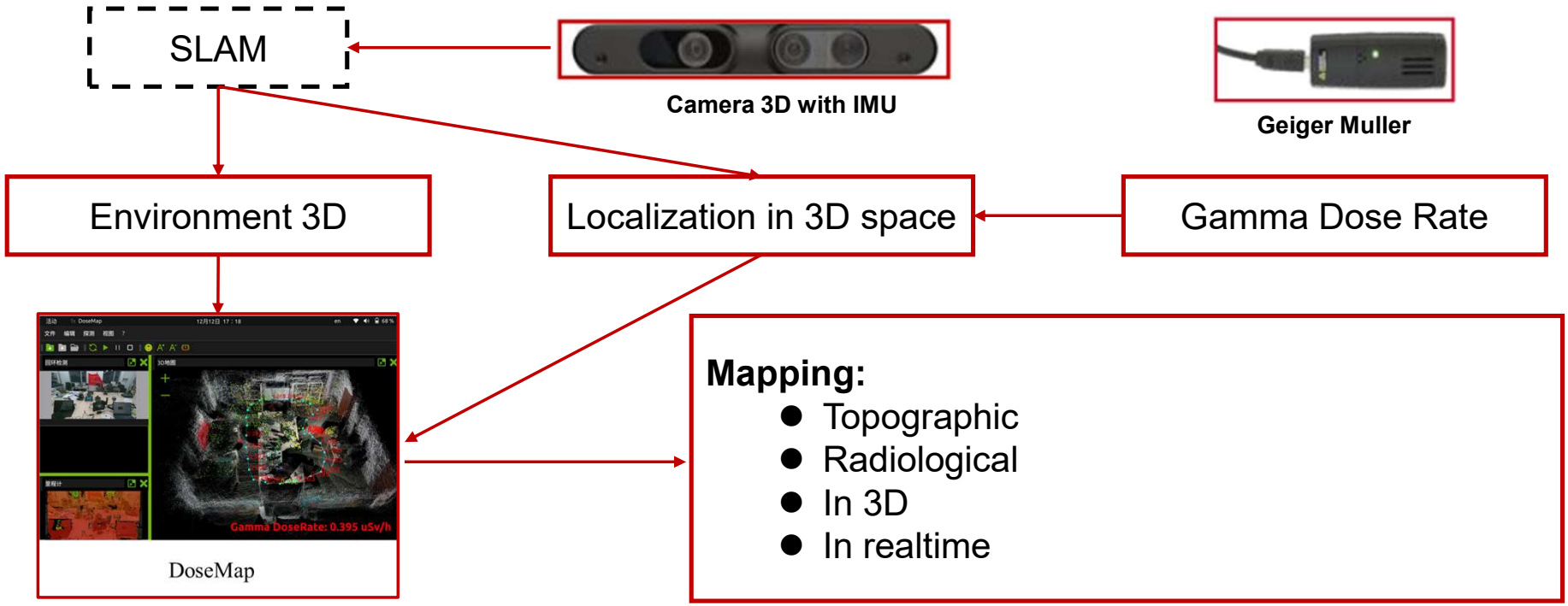
Manual record and fusion data

Radiation Mapping Mode

single measurement automatic fusion scene and radiation information

Methodology Overview

- **VSLAM: RGBD camera for 3D mapping, trajectory tracking**
- **Gamma dose module: Hot-pluggable G-M tube**
- **Data fusion: Timestamp synchronization, integral path midpoint**



Methodology Overview

VSLAM : abtain scene and localize detection trajectory and pose

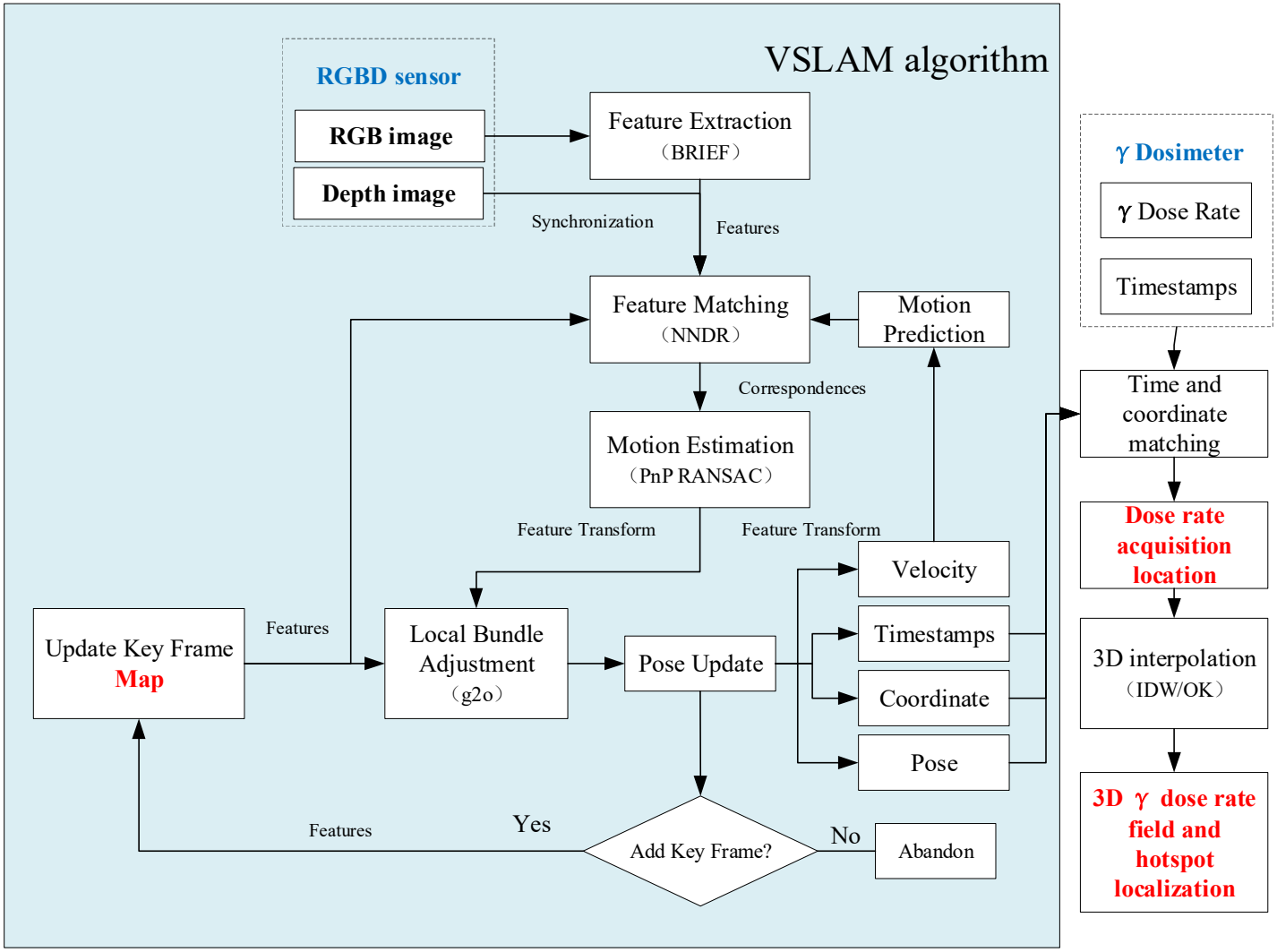
Cheap and efficient to get scene information.

γ Dosimeter : get γ dose rate information

Cheap and easy to access.

Data Fusion : achieve γ radiation dose rate field, scene structure, hot spot localization, et al.

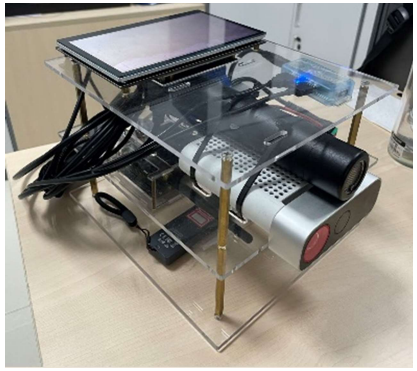
Automatically to get dose rate field and use gradient to locate hot spot.



Practical Proposal &Implementation——Hardware DoseMap

Idea

Practices



Version 1

Version 2

Version 3

Outlook on Workflow

(Handheld)

3D Model

Trajectory Location

Dose Rate Info

3D Model Interaction, segmentation and Semantic Recognition

3D Radiation Field and Applications

On-site Digital Terminal

Dimension Measurement and Annotation

Recognition and Perception

Hotspot Localization and Source Term Inversion

Path Planning

Multi-machine Collaboration

Single or multi-machine working modes \ Terminal

Support Digital System \ Cloud

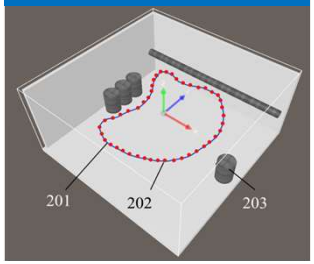
Trajectory Location

Dose Rate Info

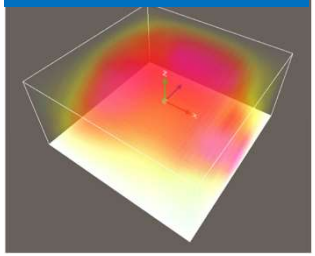
3D ALARA Interaction

Digital System

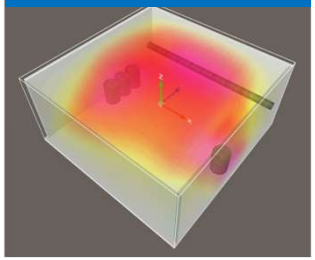
3D Topography and radiation data



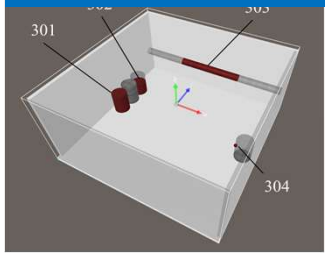
Radiation dose rate field reconstruction



3D scene and radiation field data fusion



Incremental analysis of fused data



Software developments

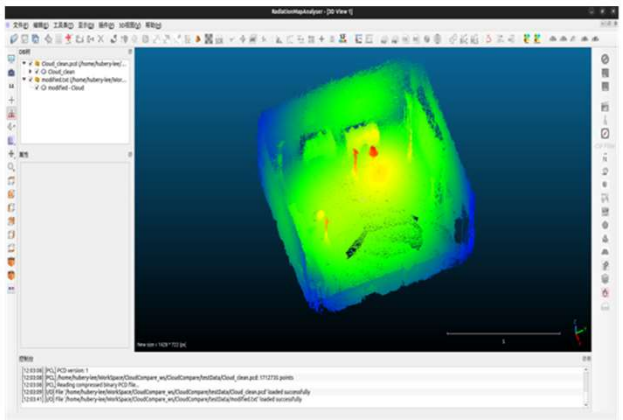
DoseMap

Measurement-End Software

●3D Scene Reconstruction Based on VSLAM

●Dose Rate Measurement Trajectory Localization

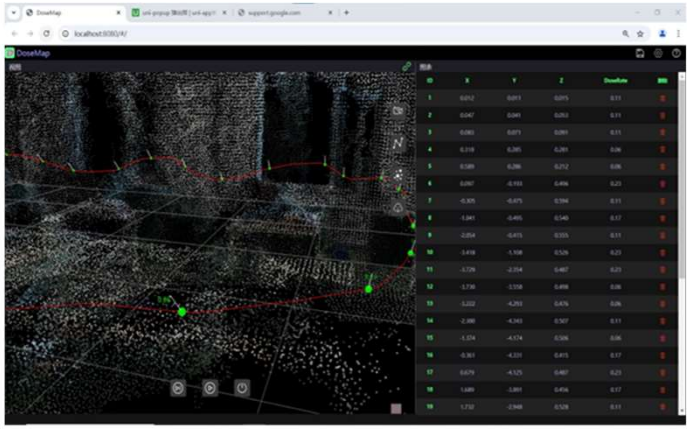
●Dose Rate Color Mapping and Label Display



RadiationMapAnalyser

Data Processing Software

- Point Cloud Cropping, Alignment, and Information Viewing
- Dose Rate Visualization
- Radiation Dose Field Interpolation and Slice Analysis
- Radiation Hotspot Localization



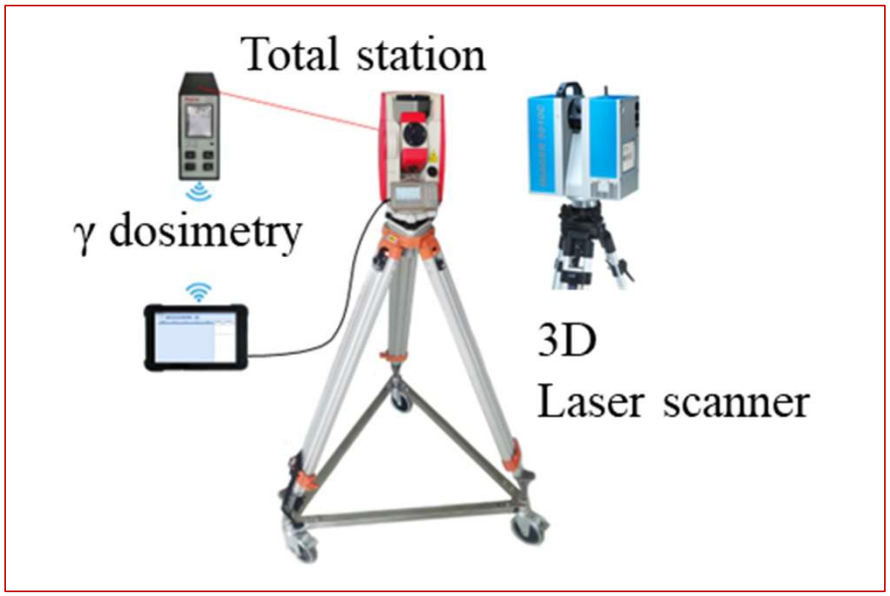
DoseMap-Web

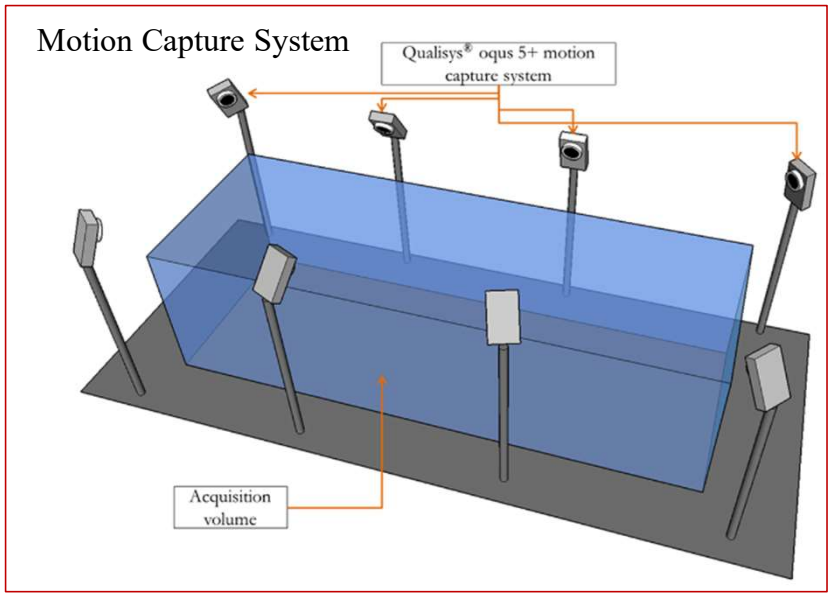
Remote Synchronized

- Remote Start and Stop
- Real-Time Display of Data
- Linux, Windows, Android and more
- Accessible via Browser

Experimental Setup

- **Location: Laboratory and Nuclear facility site**
- **Metrics: Point cloud quality, trajectory accuracy, dose error**
- **Comparison: Traditional methods vs. VSLAM approach**





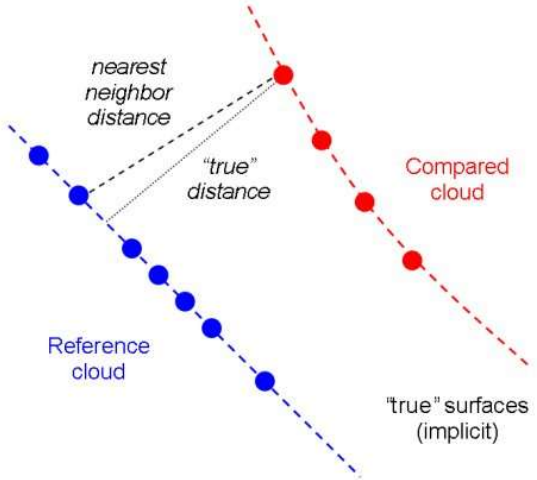
Key Features

- **Point cloud: >80% match within 0.2 m**
- **Dosimeter relative angular response error: < 15%;Mean energy response 1.01 within 65–662 keV.**
- **Trajectory accuracy:~4cm**
- **Efficiency: 26.8 times faster than traditional methods**
- **Hotspot localization error， a single γ source localization error of <0.2 m.**
- **Digital compatibility: Compatible and fast to support data to SMARP, a digital system for power plants' radiation protection.**

Scene 3D Point Cloud Quality Assessment

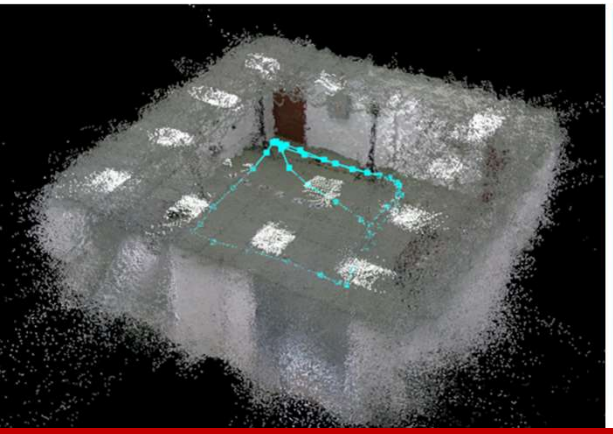
Depth Camera Parameters

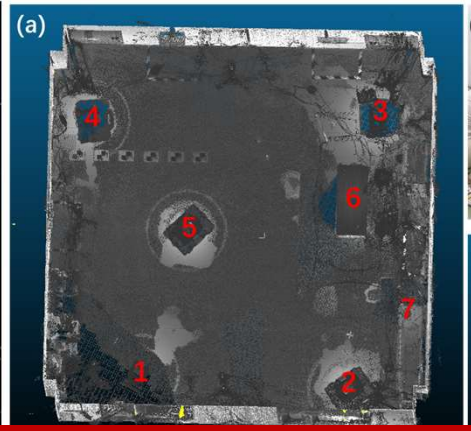
- RGB image resolution of 1280×800 pixels
- Depth image resolution of 1280×720 pixels.
- FOV is greater than 90°,90 FPS.
- Measurement range is 0.4 to 6 meters.

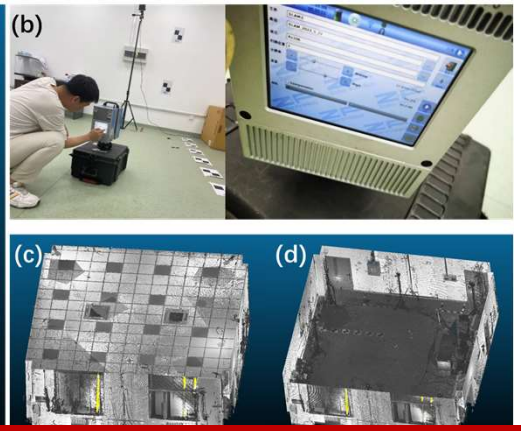


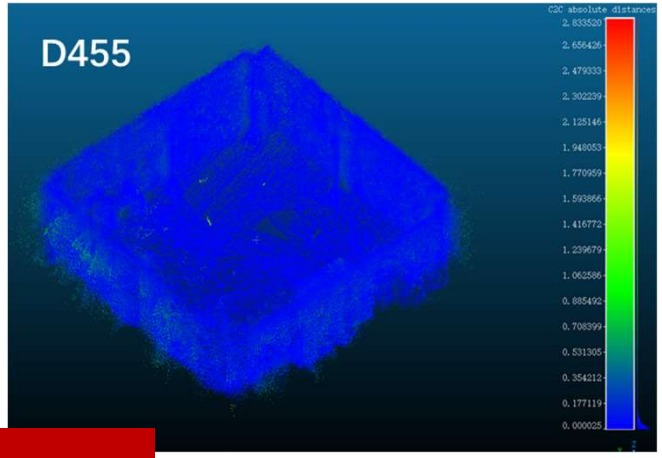
Methods:

Estimated Point Cloud → Reference Point Cloud → Distance Calculation







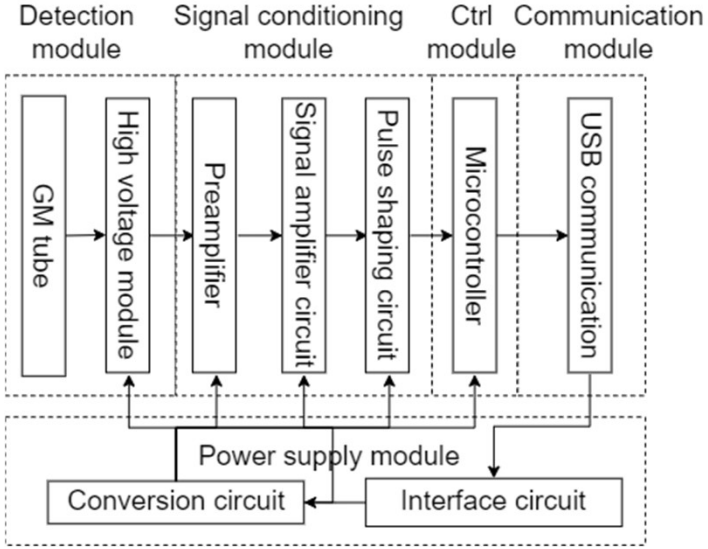


Nearest neighbor distances : 0.00–2.83 m, with over 80% less than 0.2 m.

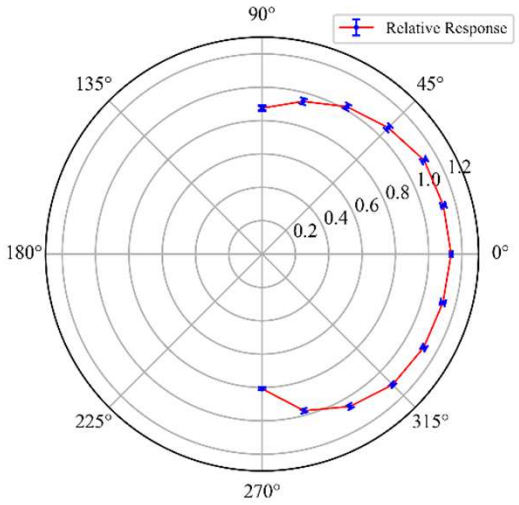
Design of γ Dosimeter

Design of hot-pluggable GM tube gamma dose rate meter

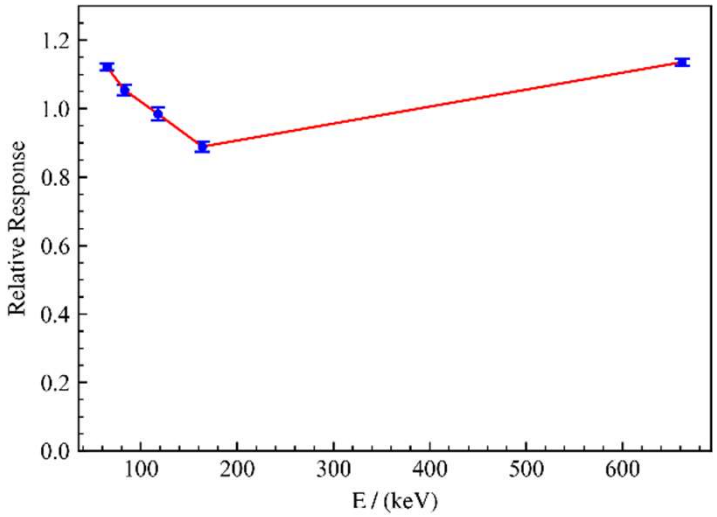
■ Diagram scheme



■ Relative angle response



■ Relative energy response



- **Total Mass**: < 200 g
- **Measurement Range**: <10mSv/h
- **Power Consumption**: 10 mW

- **Relative angular response error**: < 15%, except for areas blocked by the equipment.
- Relative mean energy response is 1.01 within 65–662 keV.

Trajectory Localization Accuracy Assessment

Methods at Labs:

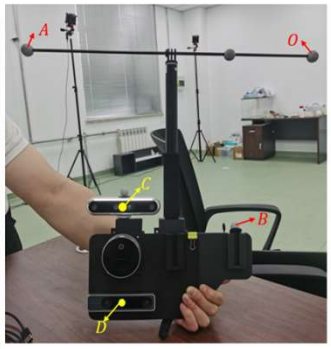
- **Trajectory Data Acquisition**
  - Reference trajectory: motion capture system
  - Estimate trajectory: our developed device
- **Match and calculate the error of two tracks**
  - Absolute translation error

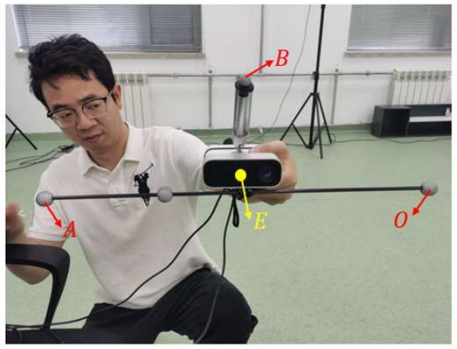
$$\mathrm{ATE}_{\mathrm{all}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \| \log(\mathbf{T}_{\mathrm{gt},i}^{-1}\mathbf{T}_{\mathrm{esti},i})^{\vee} \|_2^2}$$

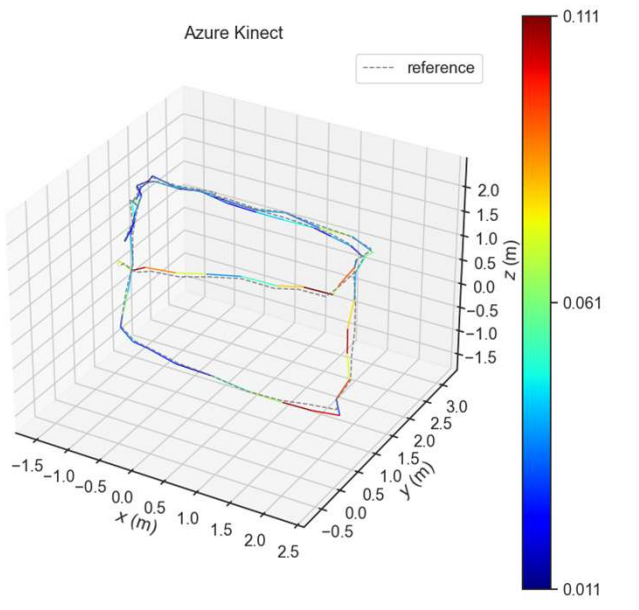
Reference trajectory

Estimated trajectory

→ Matching Umeyama algorithum → Calculate ATE





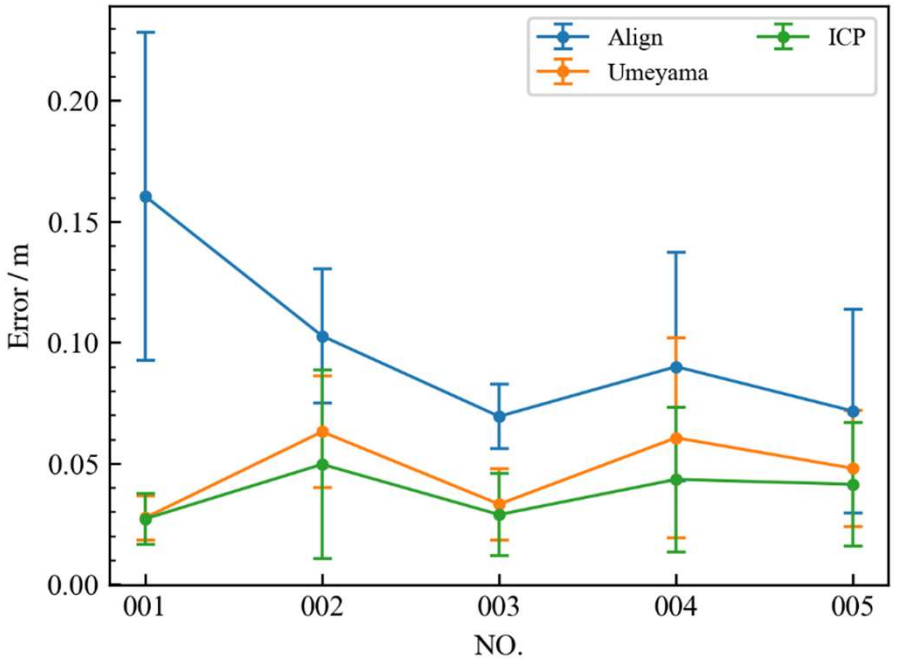


Mean trajectory localization error: 4.2 cm; standard deviation: 0.4 cm.

Trajectory Localization Accuracy Assessment

Method for On-Site Use at Nuclear Facilities

- **Measurement Devices**
  - DoseMap Radiation Mapping Equipment
  - Total Station
  - Motion Capture System (Reference Trajectory)
- **Data Processing**
  - Trajectories aligned using ICP algorithm
- **Error Results**
  - Total Station error: 0.8 ± 0.8 cm
  - DoseMap error: 3.3 ± 0.7 cm



Total Station trajectories can serve as references for DoseMap on-site nuclear power plant measurements.

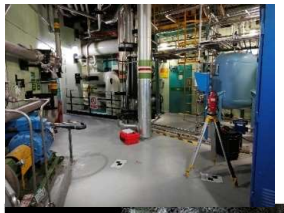
Trajectory Localization Accuracy Assessment

- **K216**

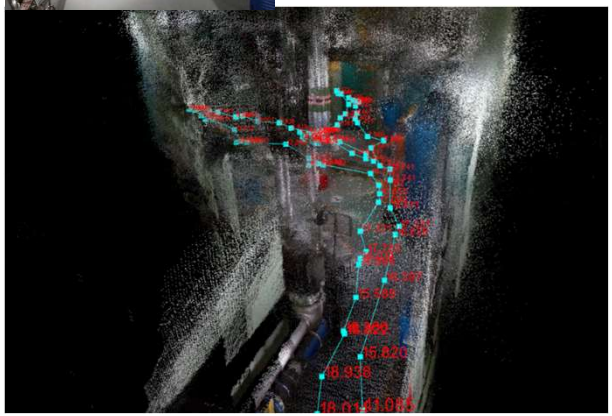
2 hotspots
①0.061mSv/h at 1m
②0.107mSv/h at 1m

ATE 6.3±1.1cm

- **W213**



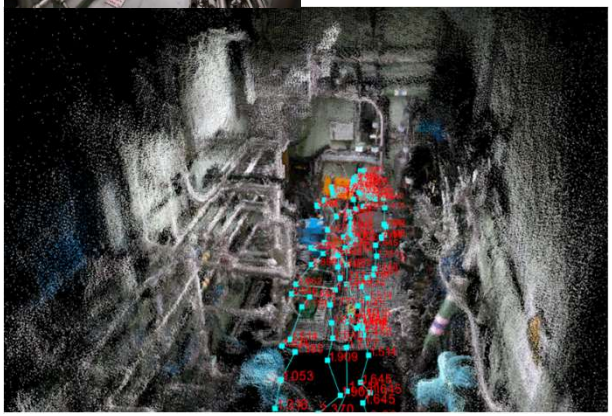
1 hotspot
12.5uSv/h at 1m



ATE 3.9 ±0.4 cm

- **Na213**

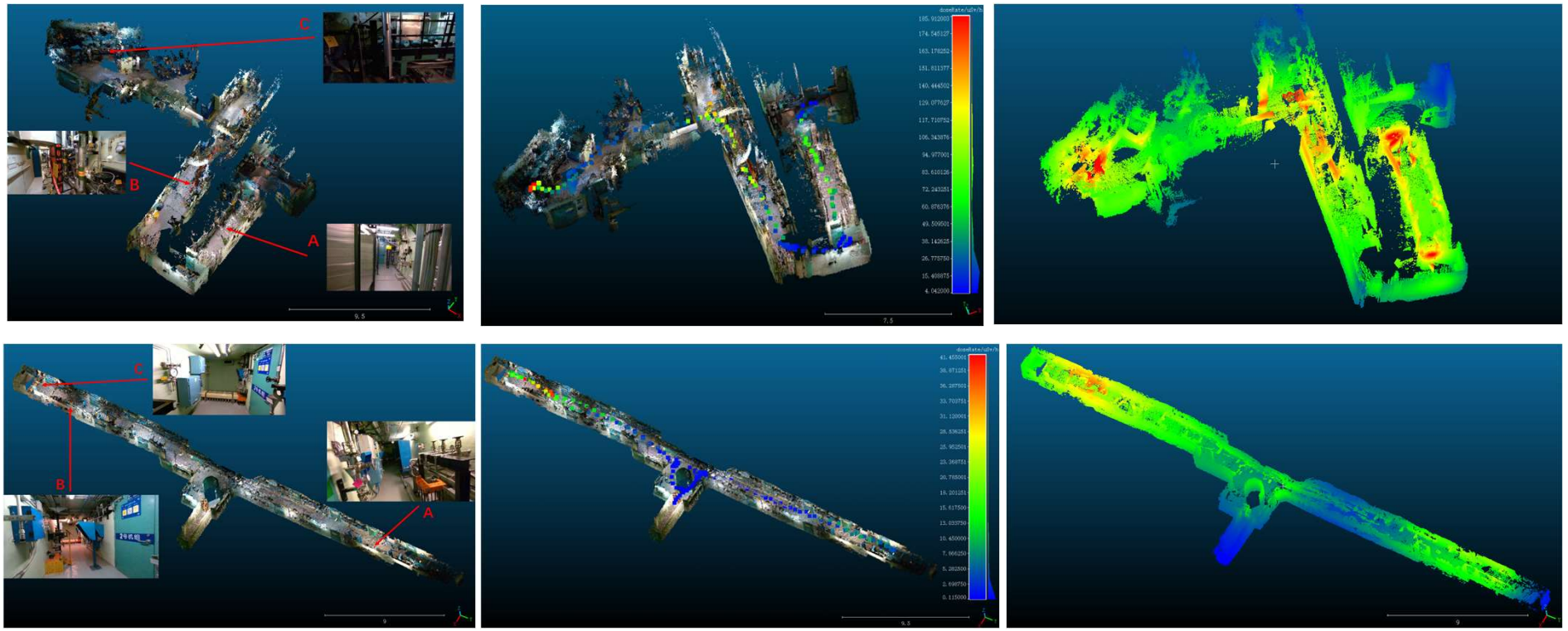
1 hotspot
0.042mSv/h at 1m



ATE 3.2±0.9cm

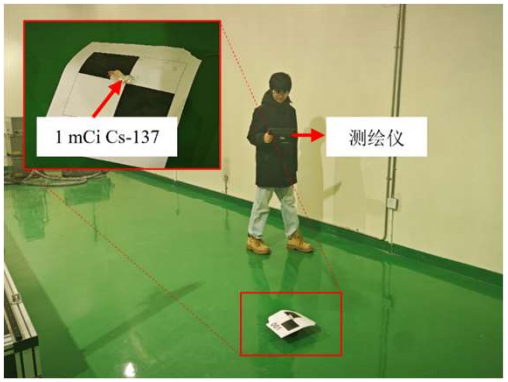
Efficiency and Hotspots Localization Testing On-site

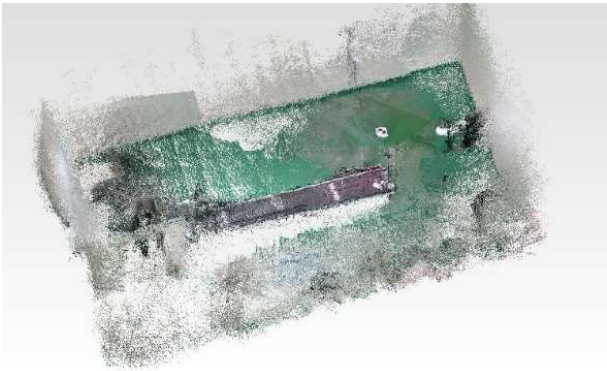
- **Efficiency—— 26.8 times faster than traditional methods**
- **Hotspots localization——Qualitative but not quantitative for multi unkown source**

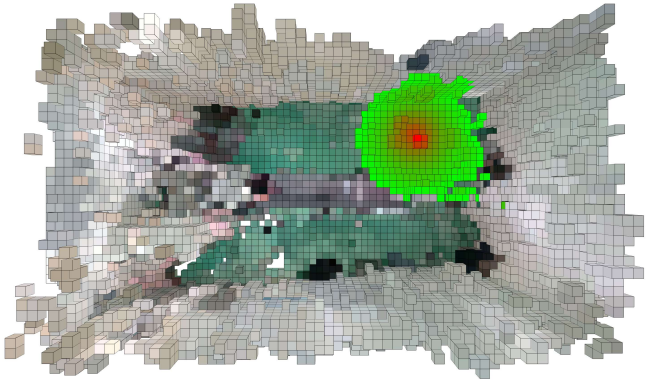


Single γ Source Localization

- **Hotspots localization——less than 20 cm for Cs-137 point source**



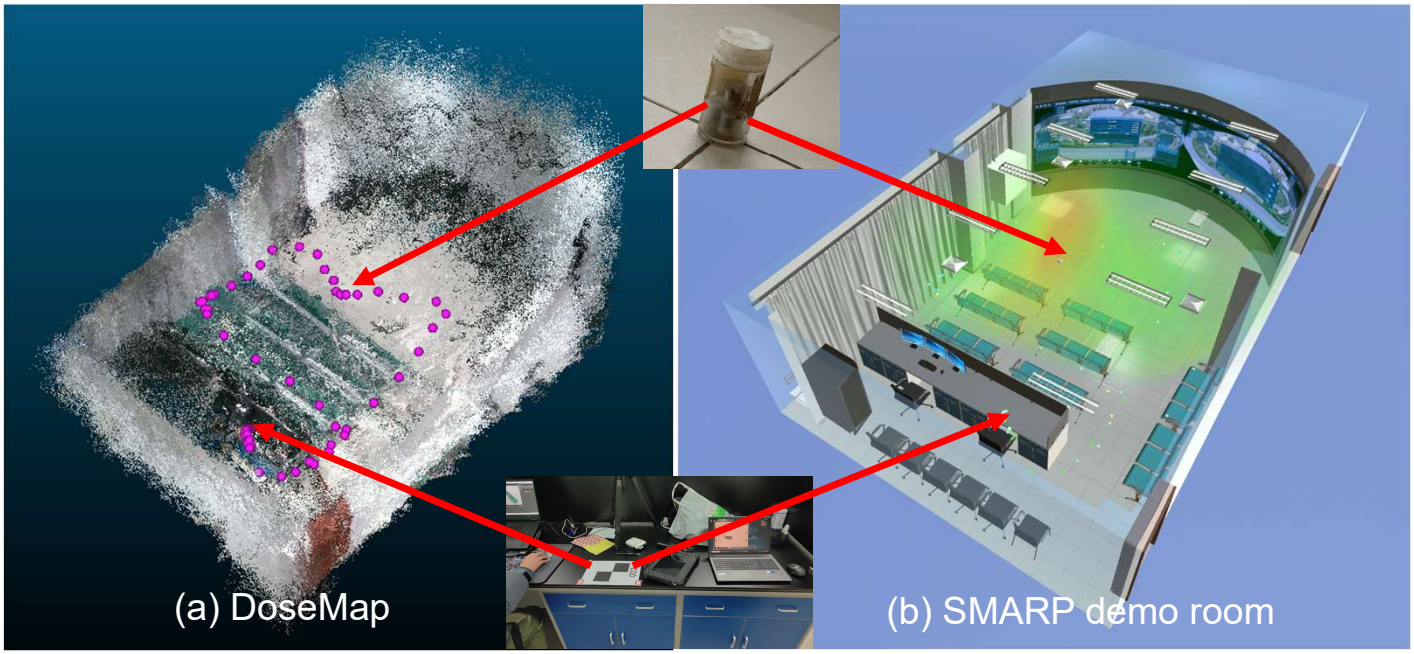


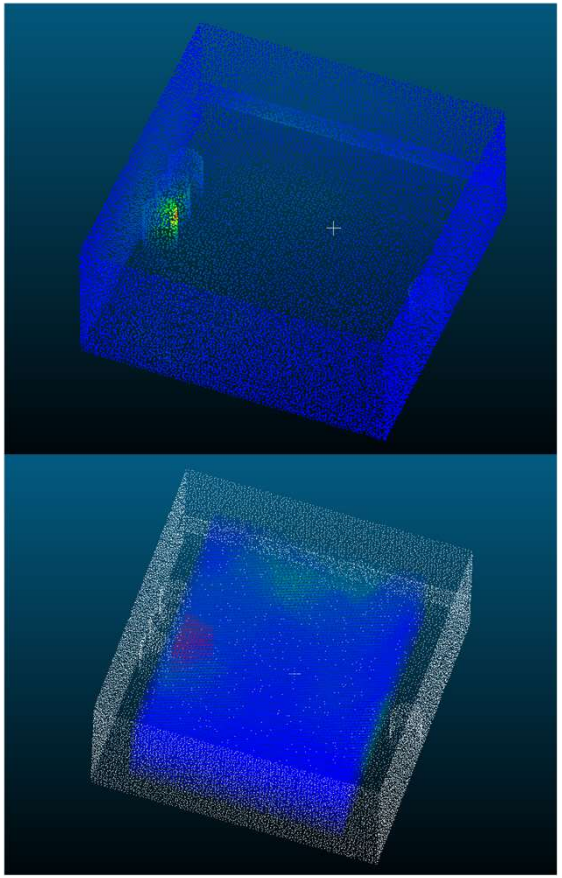


Index	Real location/m	Estimated location/m	Deviation/m
1	(-4.86, -2.28, -1.19)	(-4.81, -2.34, -1.14)	0.09
2	(1.93, -1.64, -1.08)	(2.02, -1.53, -1.00)	0.16
3	(-4.30, -0.07, -1.00)	(-4.30, 0.09, -0.94)	0.17
4	(-1.63, -1.83, -1.21)	(1.61, -1.94, -1.17)	0.12

Digital Compatibility

Linkage and Integration of DoseMap Measurement Data with the SMARP Digital Radiation Protection Support System

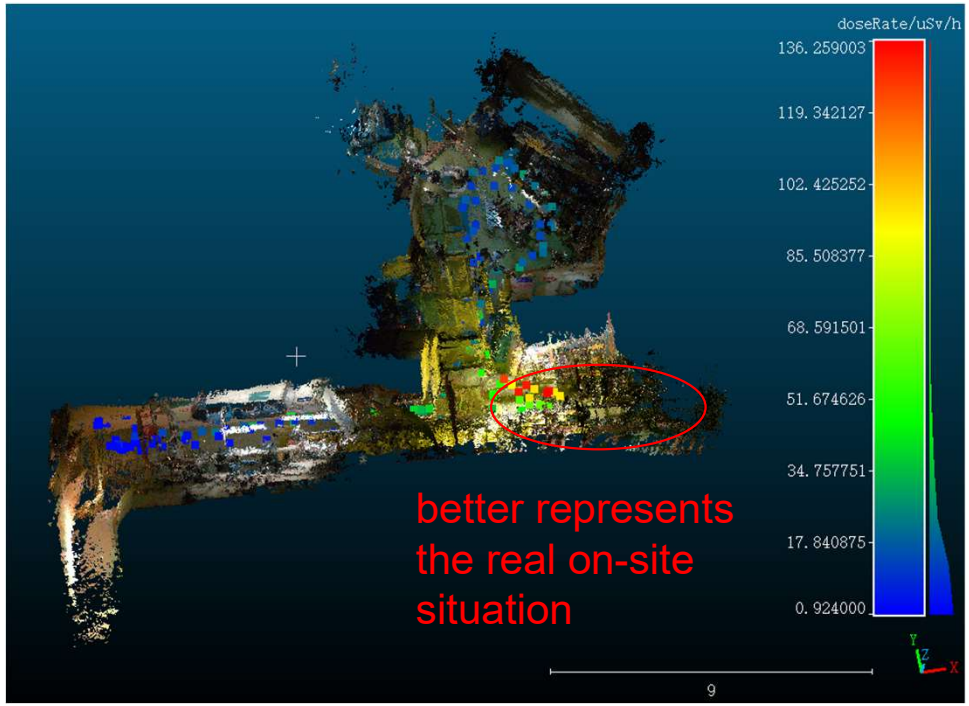




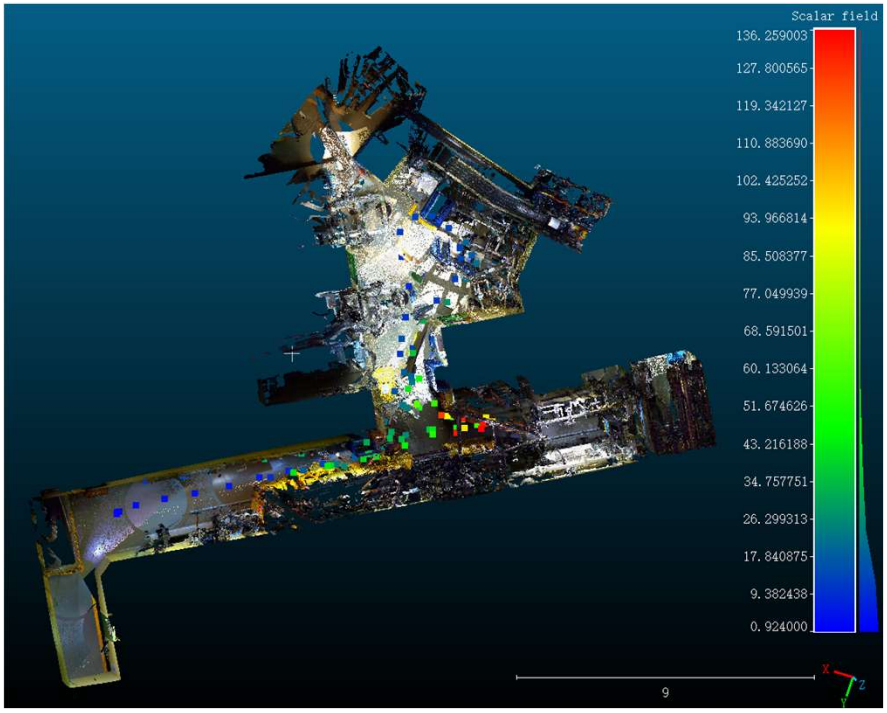
Applications in NPPs

The auxiliary building at location NB224+W258

A test was conducted in the auxiliary building at location NB224+W258 to integrate the mapping data with the SMARP system. By fixing the data acquisition starting point, a fixed coordinate transformation matrix was established, enabling seamless alignment of the mapping data with the SMARP system.



DoseMap measurement



Signed to SMARP system

Applications in NPPs

■ Residual Heat Removal Heat Exchanger Maintenance Area

The radiation fields were measured before and after the construction of the shielding structure.

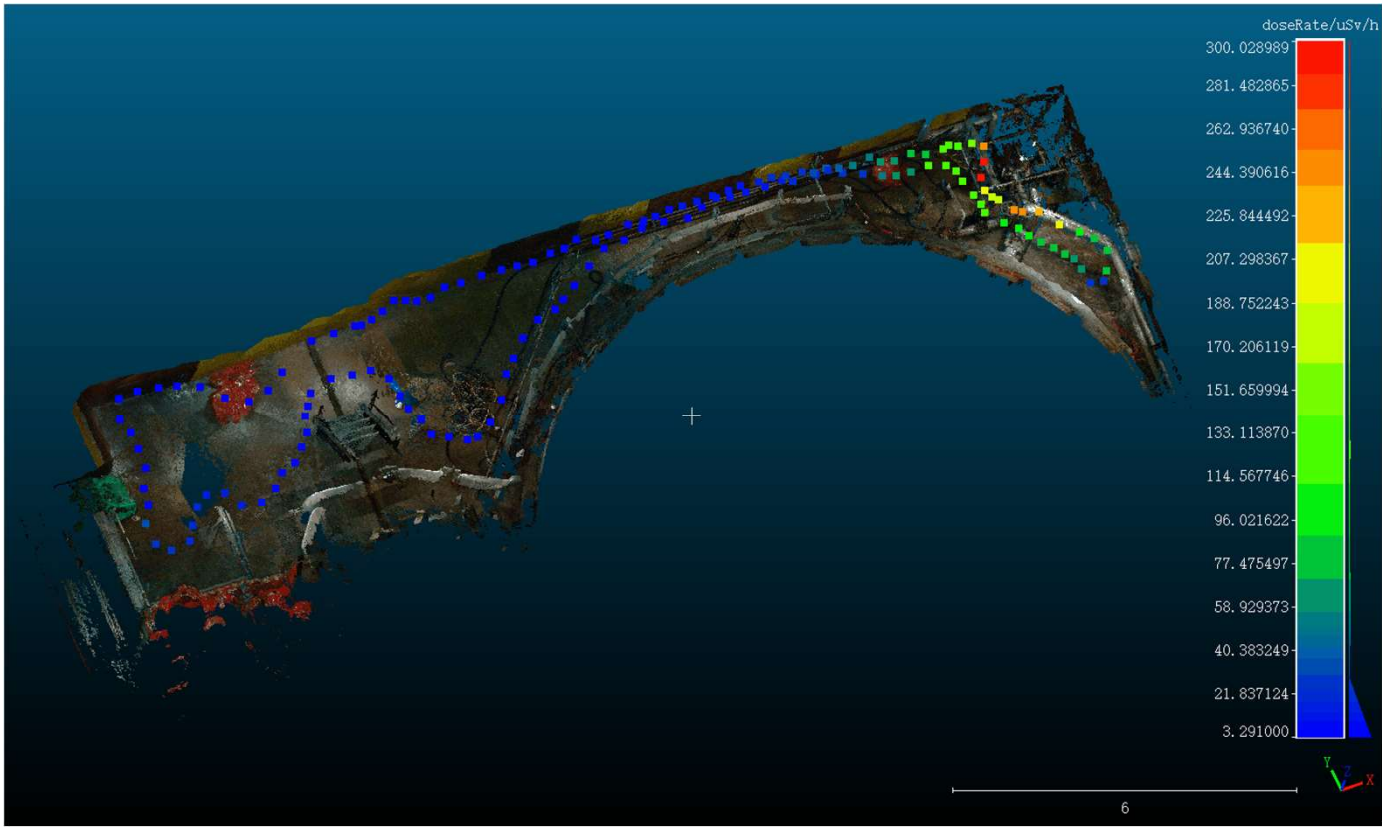
As shown in the figure on the right, the radiation field distribution after the shielding construction can be used to guide on-site operations to stay in low-dose areas and avoid high-dose regions.

Applications in NPPs

■ Periphery of the Refueling Water Tank

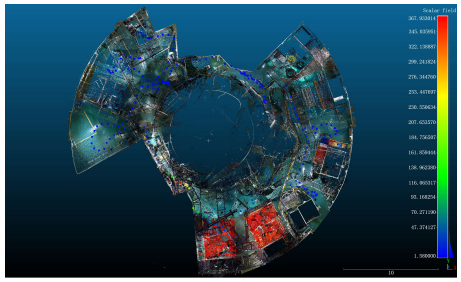
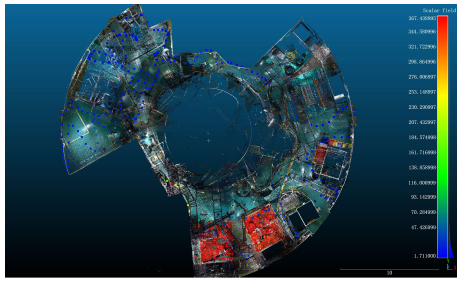
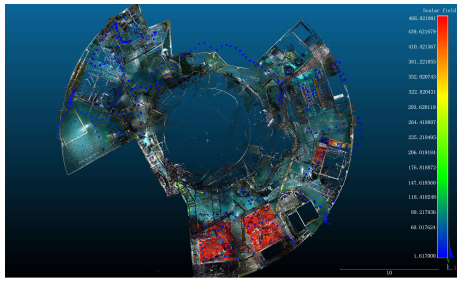
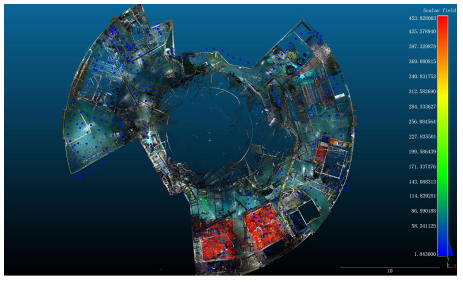
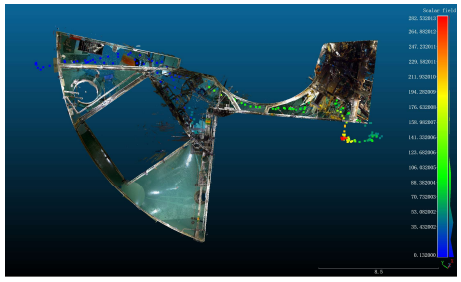
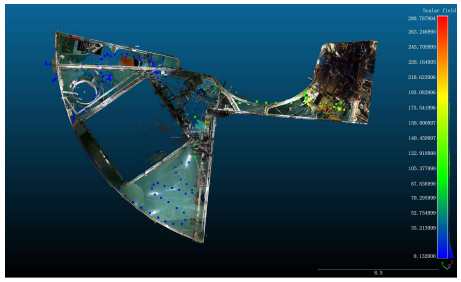
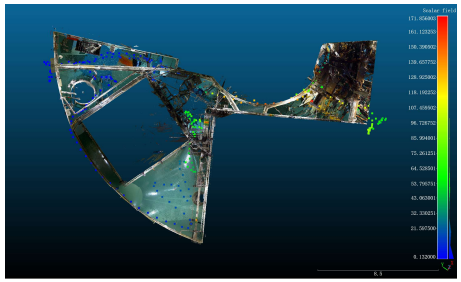
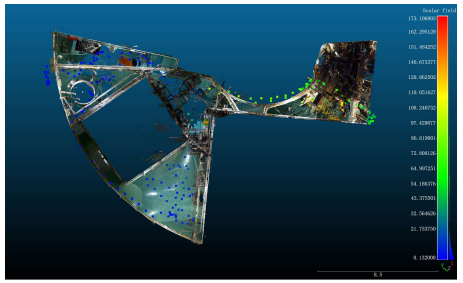
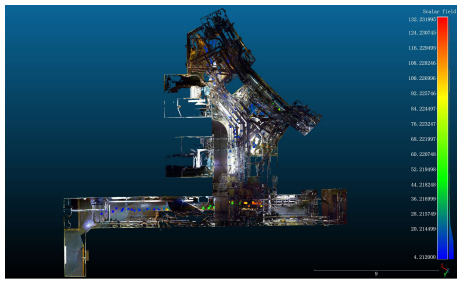
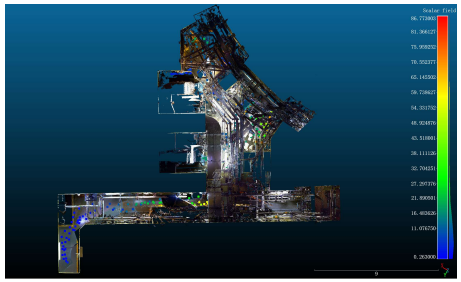
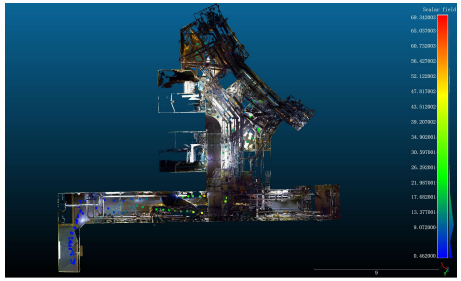
Radiation measurements were performed around the periphery of the refueling water tank area. The reconstructed model clearly represents the measured region, with dose rates ranging from 3.9 to 300 μSv/h.

Trajectory-based data allow quick identification of radiation hot spots.



Applications in NPPs

- Used to monitor and track condition variations over time

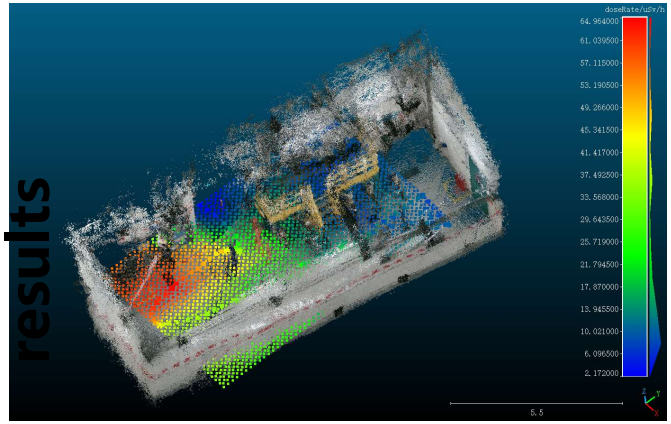
04/09/2025	09/09/2025	11/09/2025	14/09/2025
			
			
			

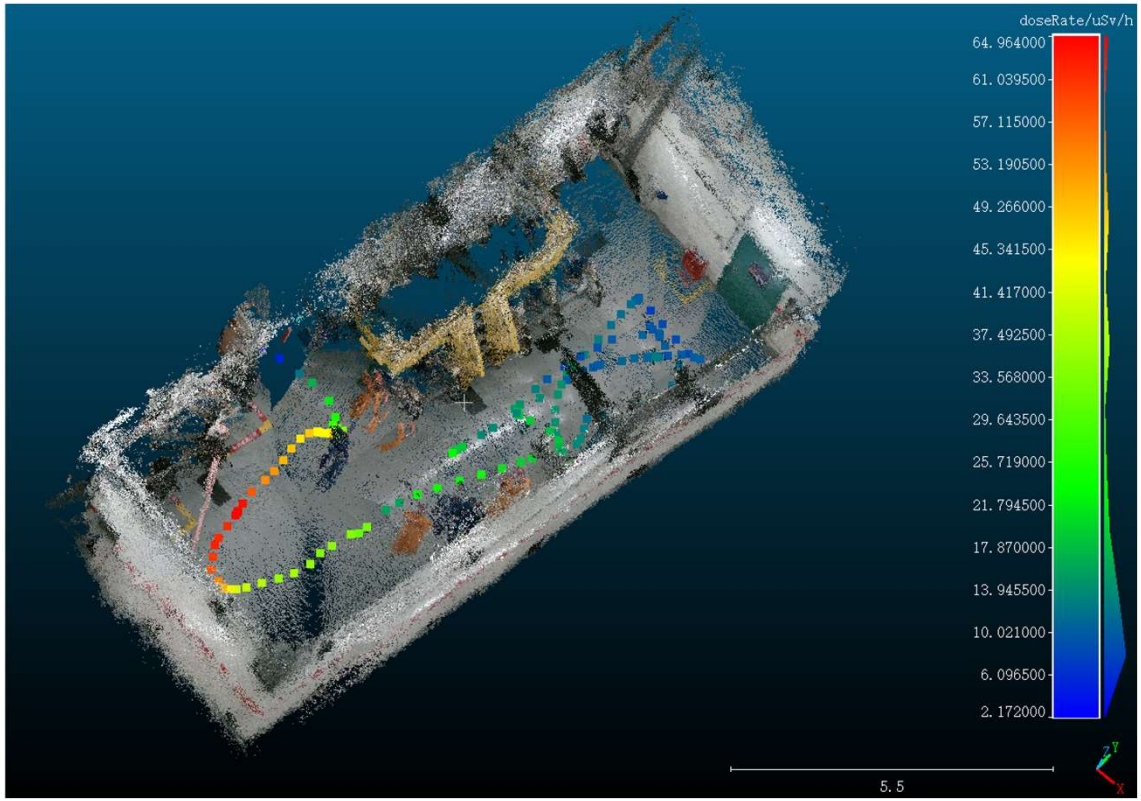
Applications in NPPs

■ Robot Carrier Measurement in the Auxiliary Building of HPR1000

Test site

Test results



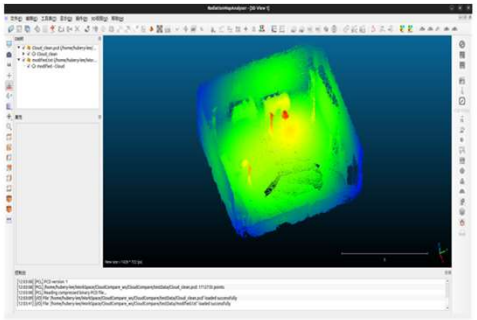


Dose rate range：about 2~65uSv/h

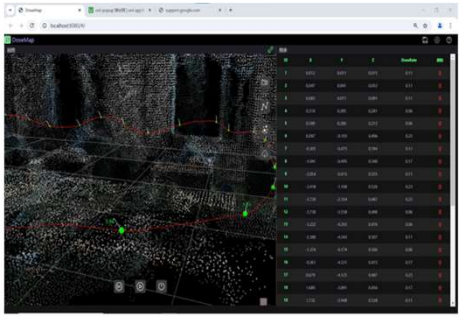
Radiation Field Interpolation and Hotspot Localization

CONCLUSION

DoseMap



RadiationMapAnalyser



DoseMap-Web

■ **Performance Evaluation**

- Measurement efficiency: 26.8 times increase in measurement efficiency compared to traditional methods.
- Trajectory localization accuracy: ~4 cm, and
- Hotspot localization error， a single γ source localization error of <0.2 m.
- Digital compatibility: Compatible and fast to support data to SMARP.

■ **Future Improvements**

Future work will try the LVIO-SLAM coupled with the spectrometer and gamma camera, expected to suit the outside scene and remotely access the radiation source information.

THANK YOU!
ANY QUSTIONS?

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