Nuclear Physics Conference 2025

Development of a gamma radiation detector system for localisation and mapping of distributed sources.

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Botswana

- A middle-income country, with a population of around 2.5 million people.

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- A major diamond producer.

Botswana

Botswana Institute for Nuclear Science and Technology (BINST)

BIUST and other local stakeholders in partnership with the IAEA to build a national facility in Botswana

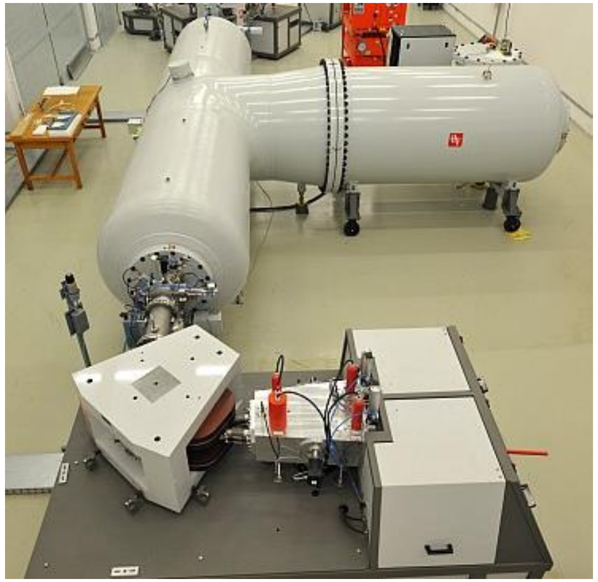
IAEA
International Atomic Energy Agency

- Nuclear Science is still at infancy stage in Botswana but it is fast developing through partnerships with the IAEA.

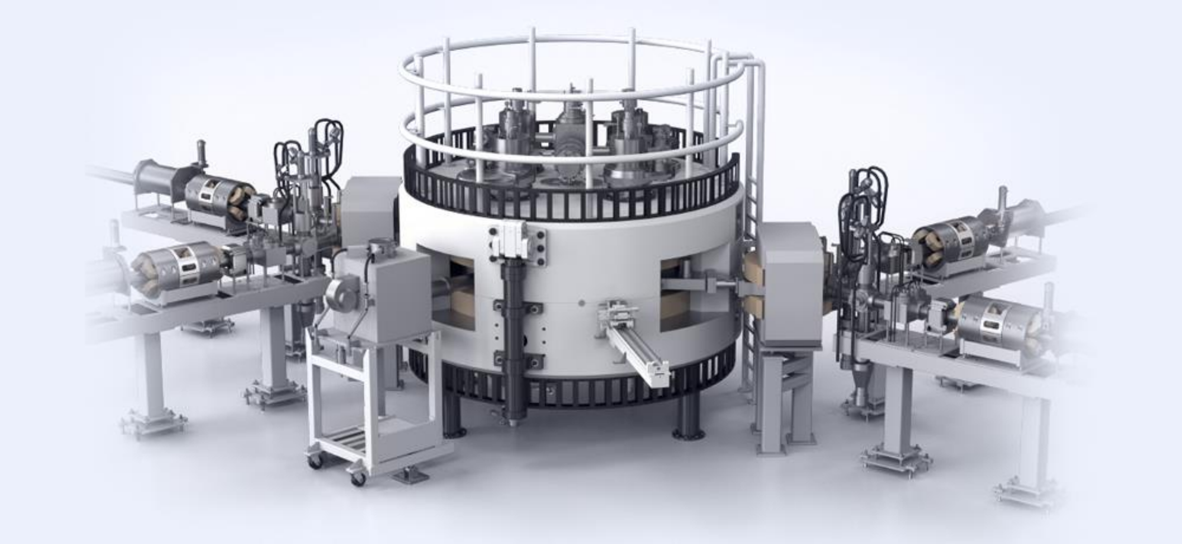
- The mandate is to build human capacity and transition from a mining-based economy towards a knowledge based economy.

Botswana Institute for Nuclear Science and Technology (BINST)

- 3 MV tandem particle accelerator for ion beam analysis.



- 18 MeV compact proton accelerator (for production of PET isotopes)



- Isotope hydrology lab
- Environmental nuclear metrology lab
- Secondary standards dosimetry lab
- Detector development lab

To be commissioned in 2 – 3 years

Development of a gamma radiation detector system for localisation and mapping of distributed sources.

“Making the invisible, visible”

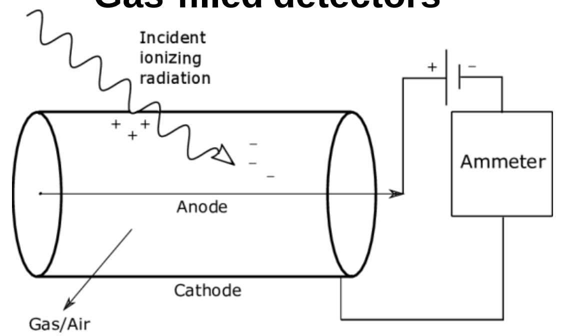
- Identification of radiation contaminated hotspots requires the use of radiation detectors.

- Potential applications in nuclear decommissioning and environmental monitoring.

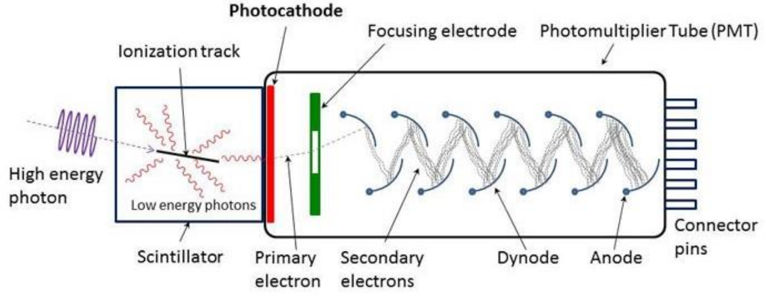
- Localising distributed sources is challenging due to a 'blurring' effect that overestimates the source's edges.

- A scanning system and techniques are proposed, that will allow for more accurate source localisation and mapping.

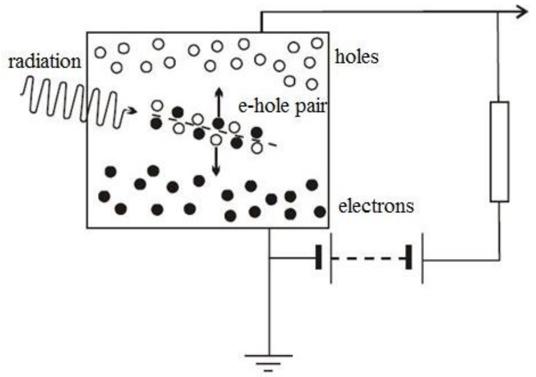
Gas-filled detectors



Scintillation detectors



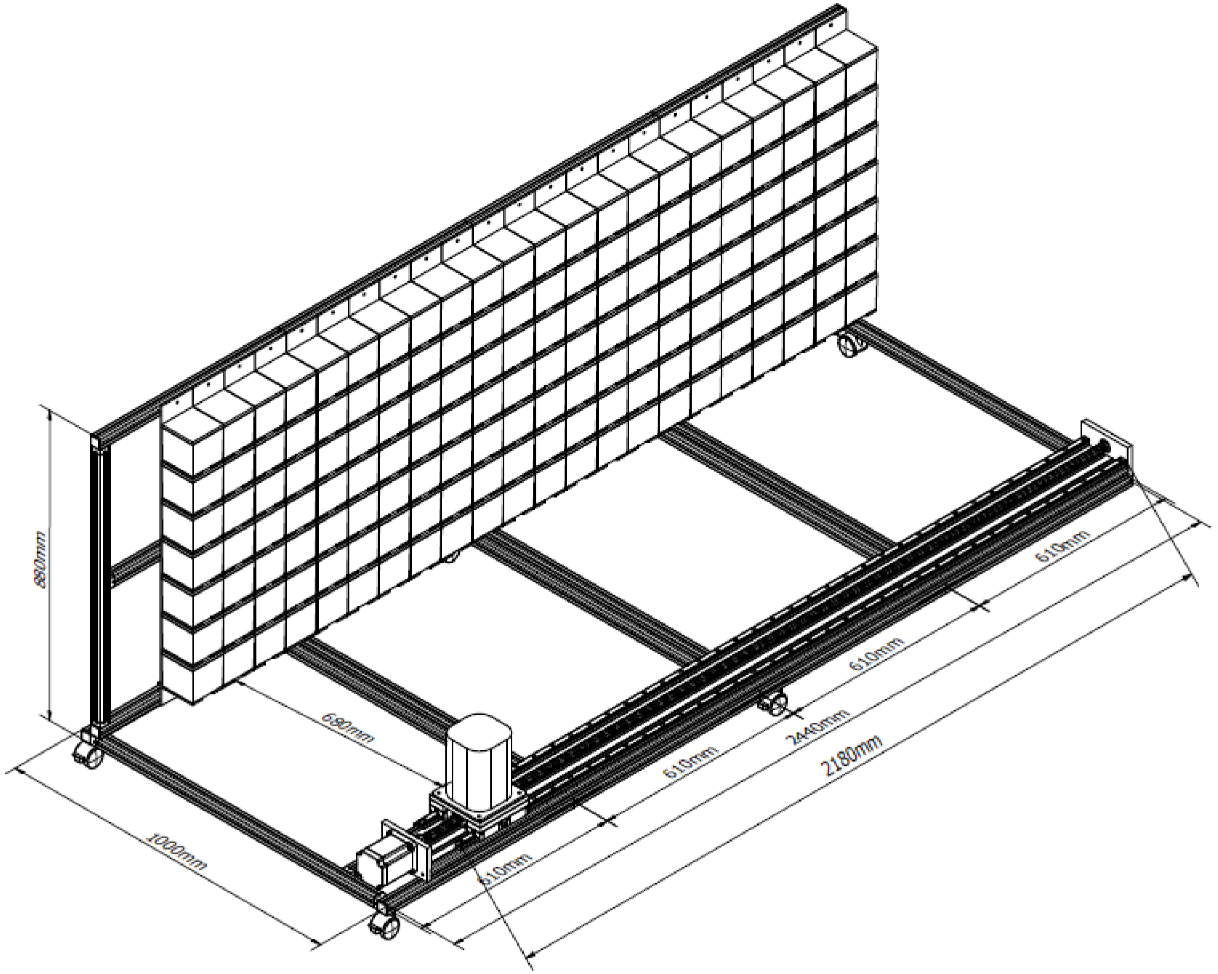
Semiconductor detectors



Monira, S., & Brücken, E. (2020). Charging-up Behaviour of MicroPattern Gaseous Detectors.
https://commons.wikimedia.org/wiki/File:PhotoMultiplierTubeAndScintillator.jpg

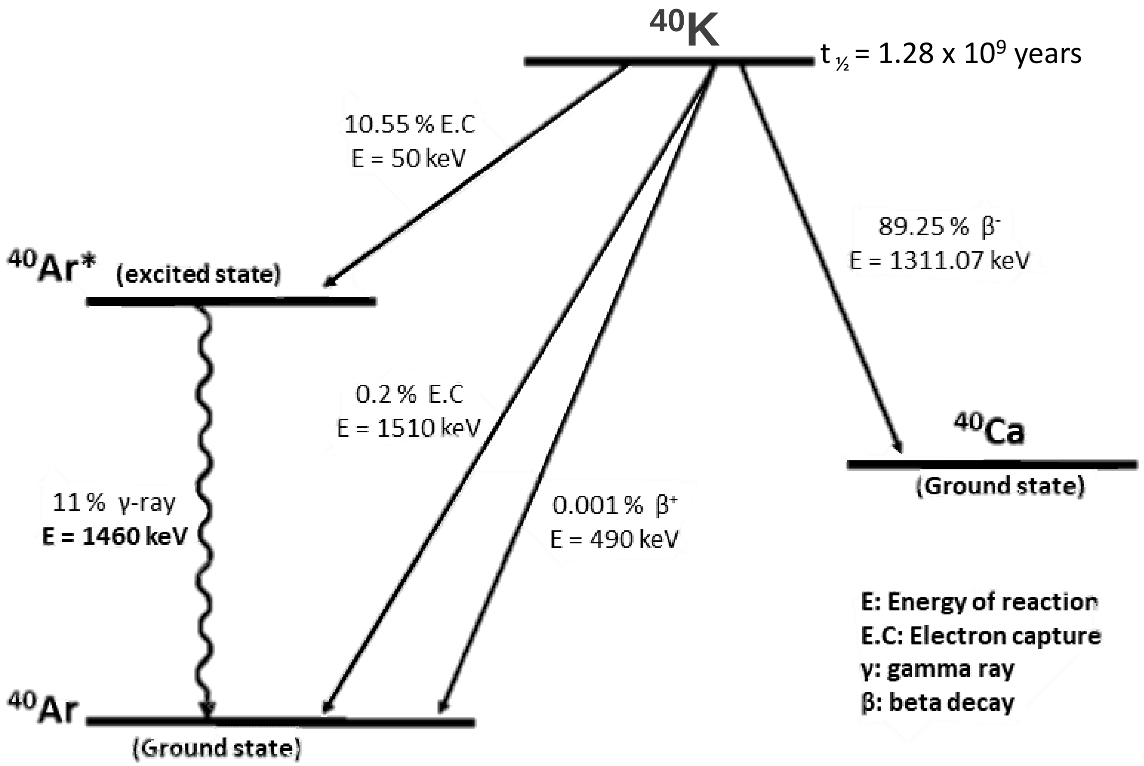
Simulating a radiation-contaminated environment

- A radiation contaminated wall was simulated using 10 cm acrylic boxes.
- Dimensions of the wall: 2.18 m x 0.88 m.
- The boxes were filled alternately with a radioactive source and a low radiation activity material.
- Different source configurations/ patterns were explored.



Radioactive source

- ^{40}K, is a naturally occurring radioisotope found in potassium-rich materials.
- Potassium sulphate (K_2SO_4) fertiliser containing 50% potassium was used as a radiation source and sand as the control.
- Directional detection of the 1460 keV γ-rays can help localise and map out the sources.



Leutz, H., Schulz, G., and Wenninger, H.: The decay of potassium-40, Z. Phys., 187, 151–164, https://doi.org/10.1007/BF01387190, 1965.

Choice of detector

Things to consider:

- ✓ High detection efficiency
- ✓ Good energy resolution and spatial resolution
- ✓ Compact and portable

- Bismuth Germanate (BGO) efficiently absorbs γ-rays.

  Bismuth, z = 83

  Density = 7.13 g/cm^3

- BGO crystal (10.125 cm x 5.8 cm x 2 cm).

- Relatively fast decay time of 300 ns.

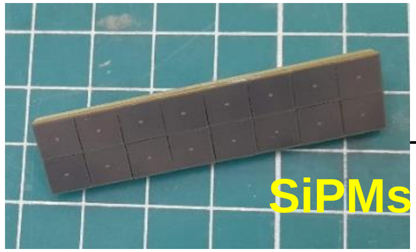
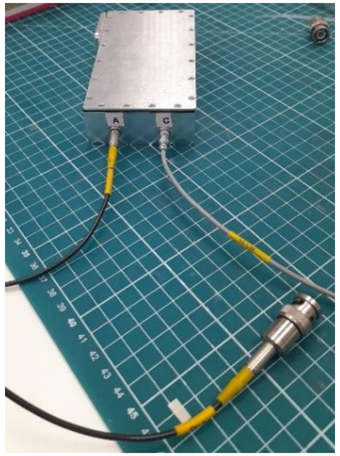


Photo-coupled to a BGO crystal using silicone grease

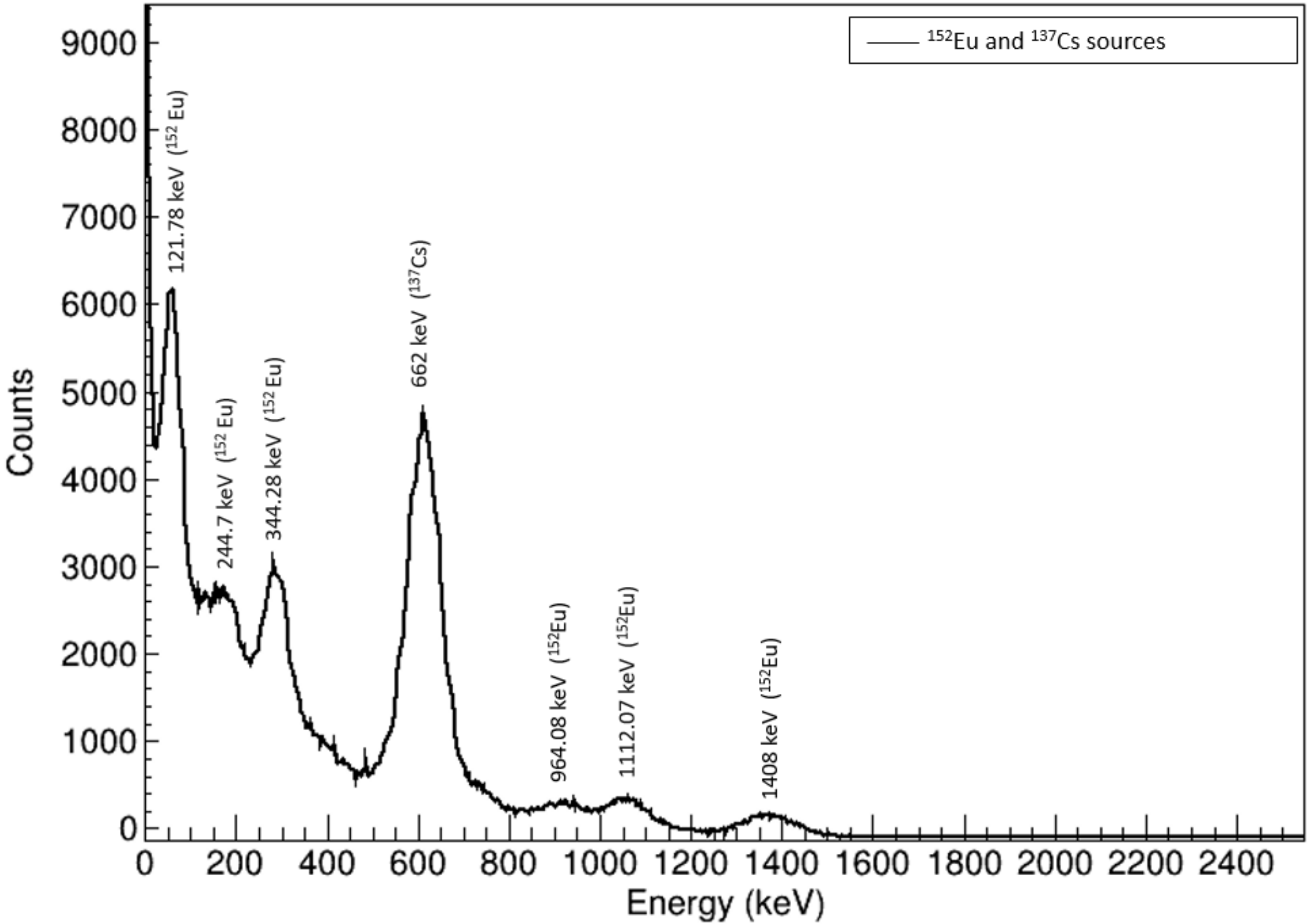
Crystal wrapped with PTFE Tape (Teflon tape) and then housed in an aluminium casing

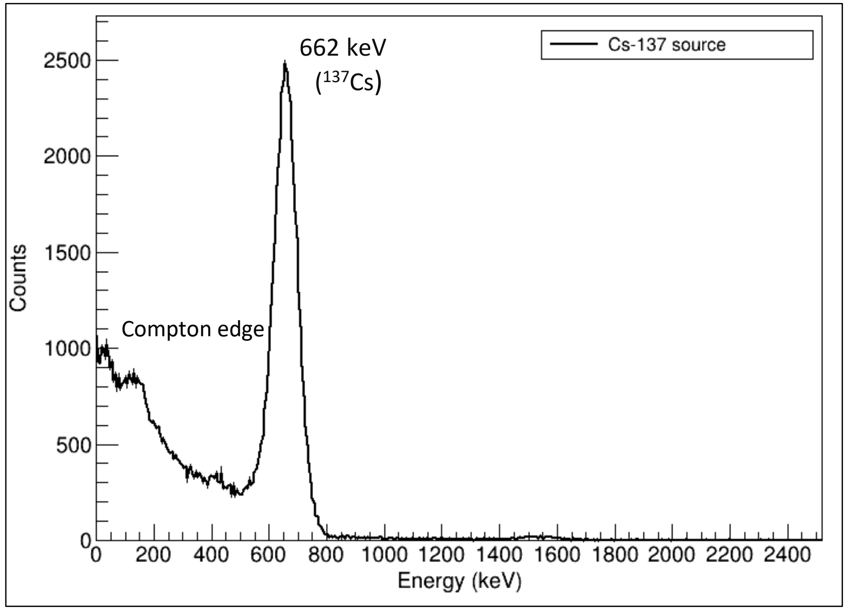


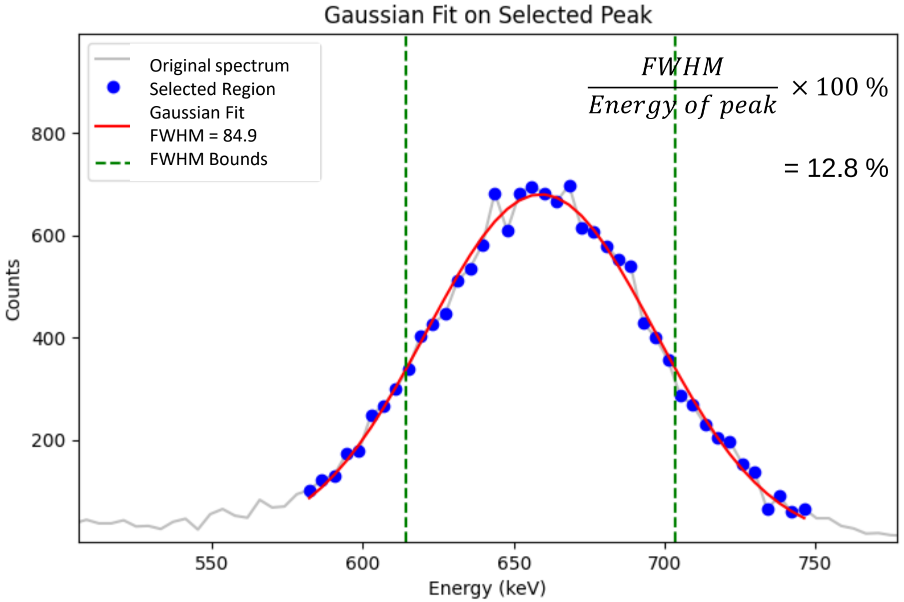
Knoll, G. F. (2010). Radiation detection and measurement. John Wiley Sons.

Detector performance

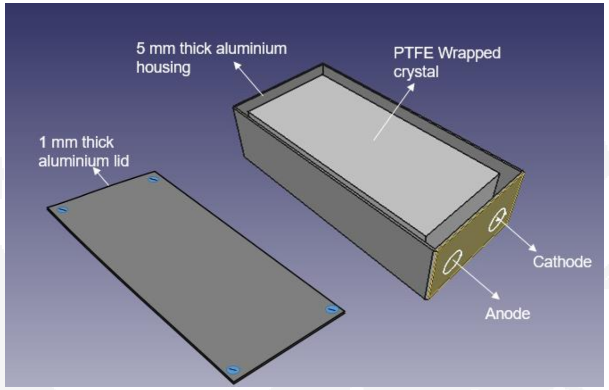
- Tested using ^{152}Eu and ^{137}Cs standard sources
- Able to detect a wide range of gamma energies.
- Energy resolution of 12.8 % @ 662 keV
- Good SNR

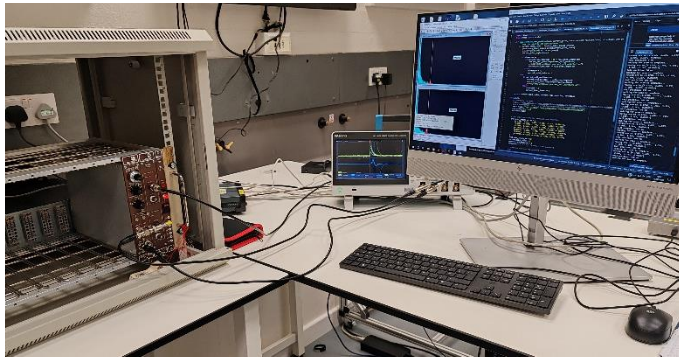






The scanning system





Scintillator detector (Bismuth Germanate)

SiPM array

Amplifier

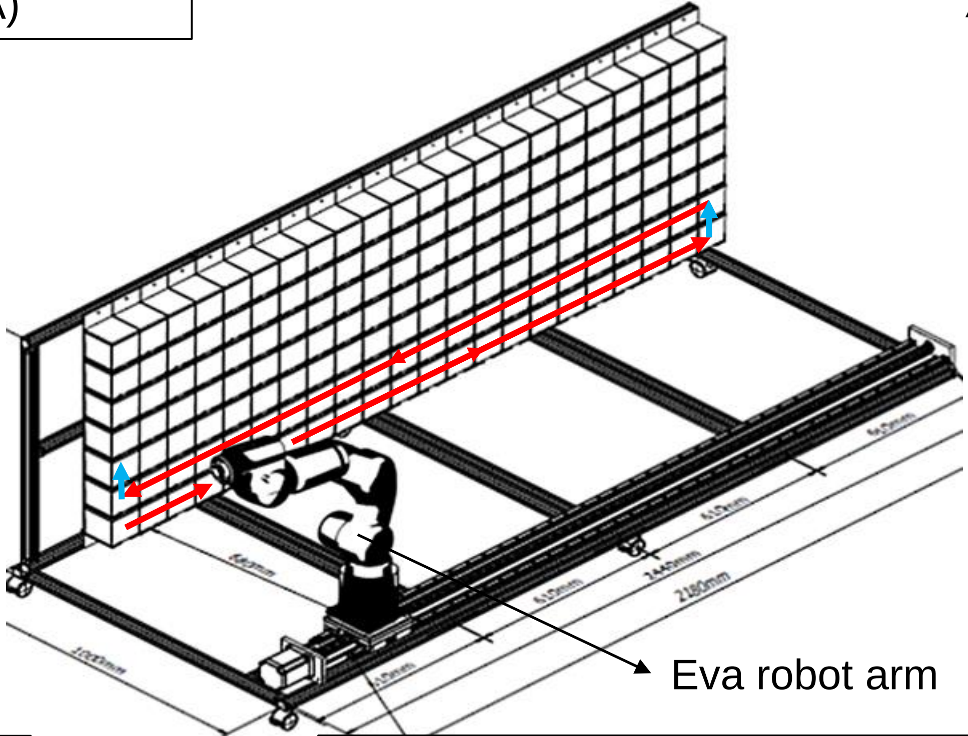
Multichannel analyzer (MCA)

Computer

Bias voltage supply

+5V output triggering robot to move to the next position.

Once the robot has moved, it sets the voltage to low which allows Maestro (Radiation data acquisition software) to fill in the next buffer.



Eva robot arm

Python job script to move the robot in a raster pattern. (Scan time: 30 seconds at each position)

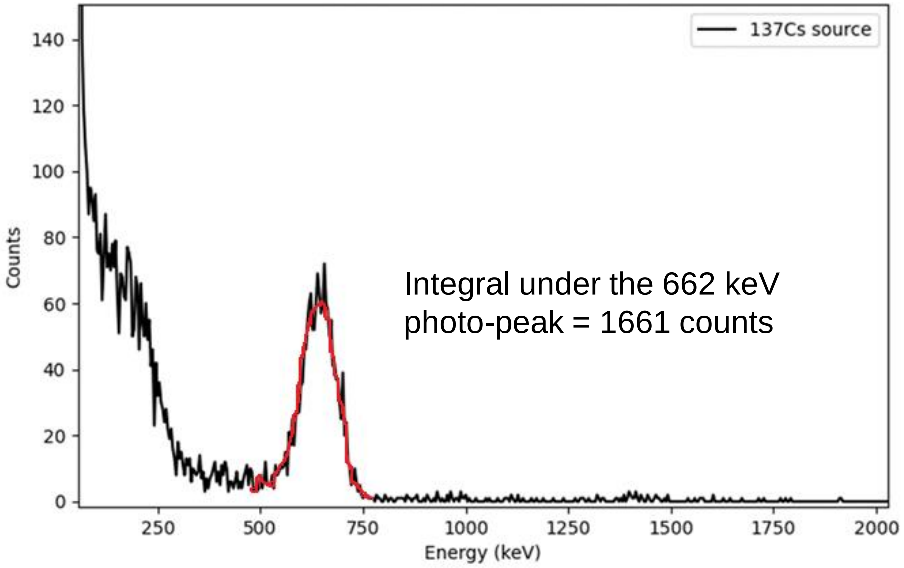
EVA robot arm

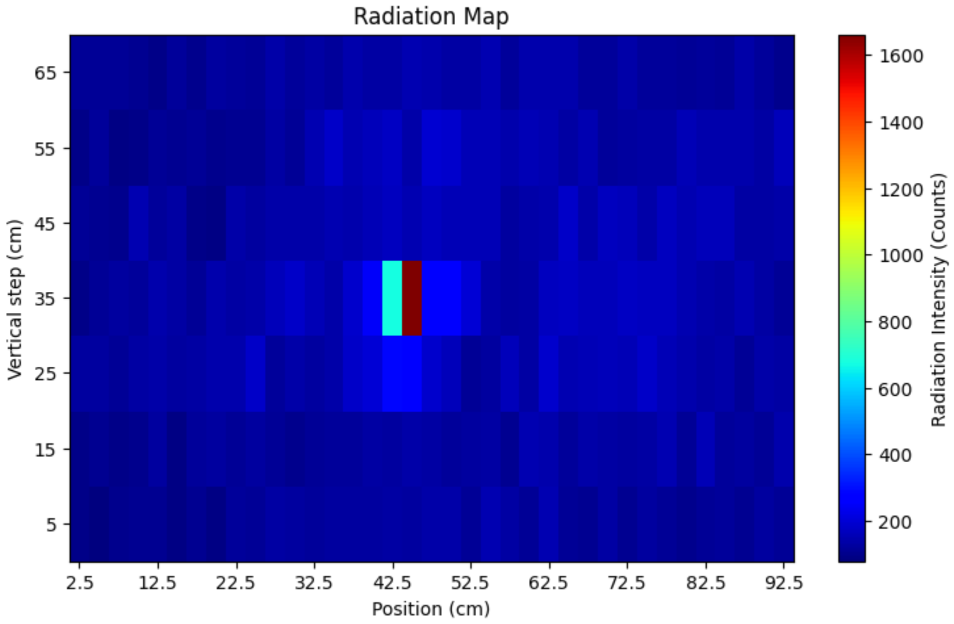
Ethernet connection

Point Spread Function (PSF)

Preliminary Results

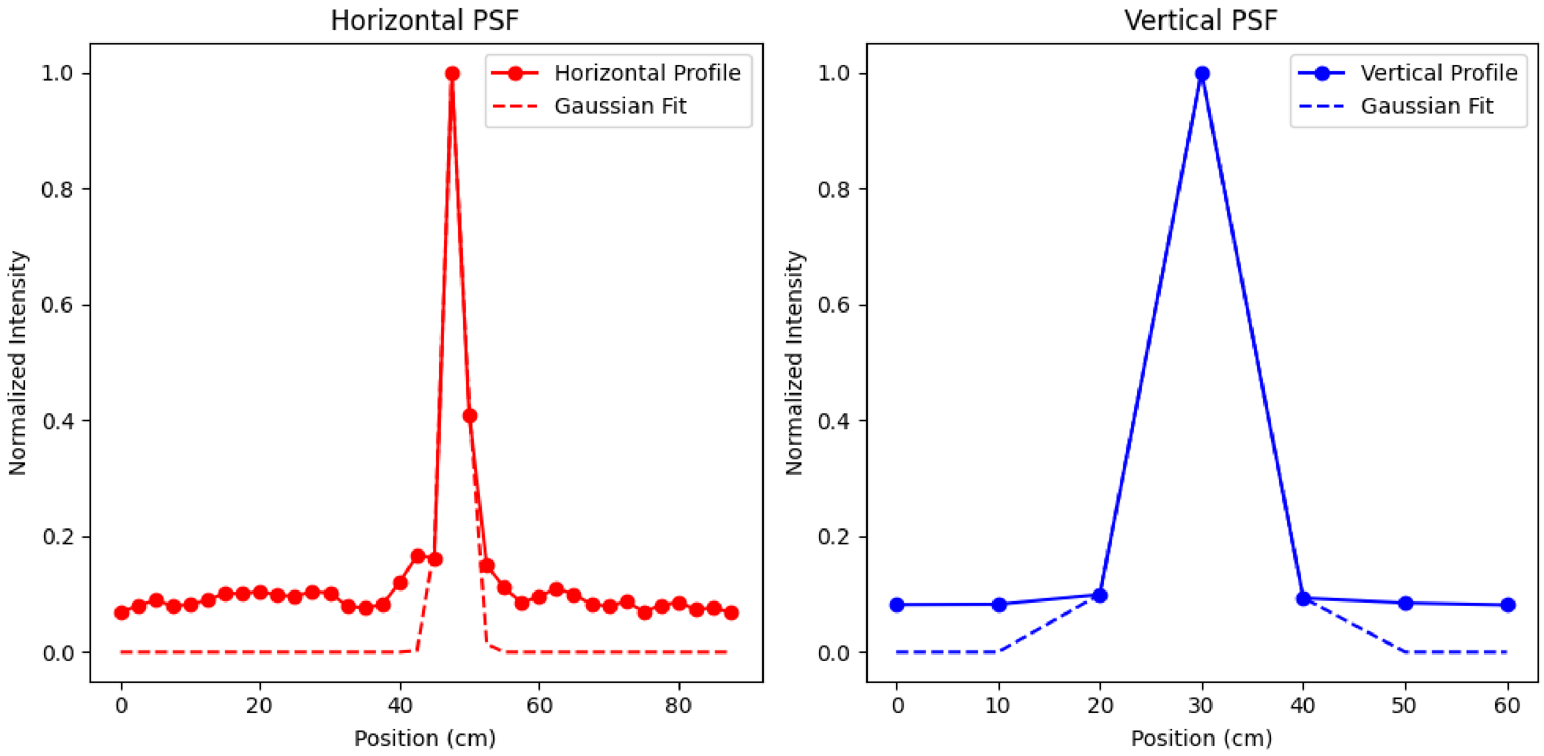
- A collimated ^{137}Cs source was used to determine the Point Spread Function.
- The detector was placed 10 cm away from the wall and moved in 2.5 cm horizontal steps and 10 cm vertical steps.
- A 2D radiation map was generated by overlaying the radiation data after background subtraction with the position data of the detector.





Point Spread Function (PSF) cont'd

Preliminary Results



$$\text{FWHM} = 2\sqrt{2\ ln2\ \sigma} \approx 2.355\sigma$$

where σ is the standard deviation obtained from the Gaussian fit.

$FWHM_x$ = 3.68 cm

$FWHM_y$ = 10.89 cm

Spatial resolution = $\sqrt{(FWHMx)2 + (FWHMy)2}$

= **11.50 cm**

σ = 4.88 cm

Image processing

- **Deconvolution**: The Richardson-Lucy algorithm was employed which uses the PSF to perform the mathematical inverse of the imaging process. It is based on the Bayesian maximum likelihood estimation.

- **Bi-cubic interpolation:** estimates the colour or intensity of new pixels based on a weighted average of neighbouring pixels, resulting in a smoother and more accurate representation of the image.

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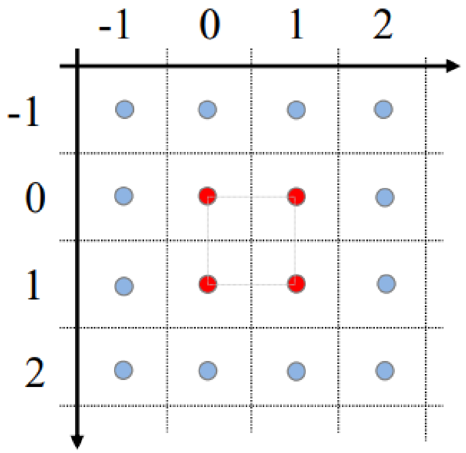
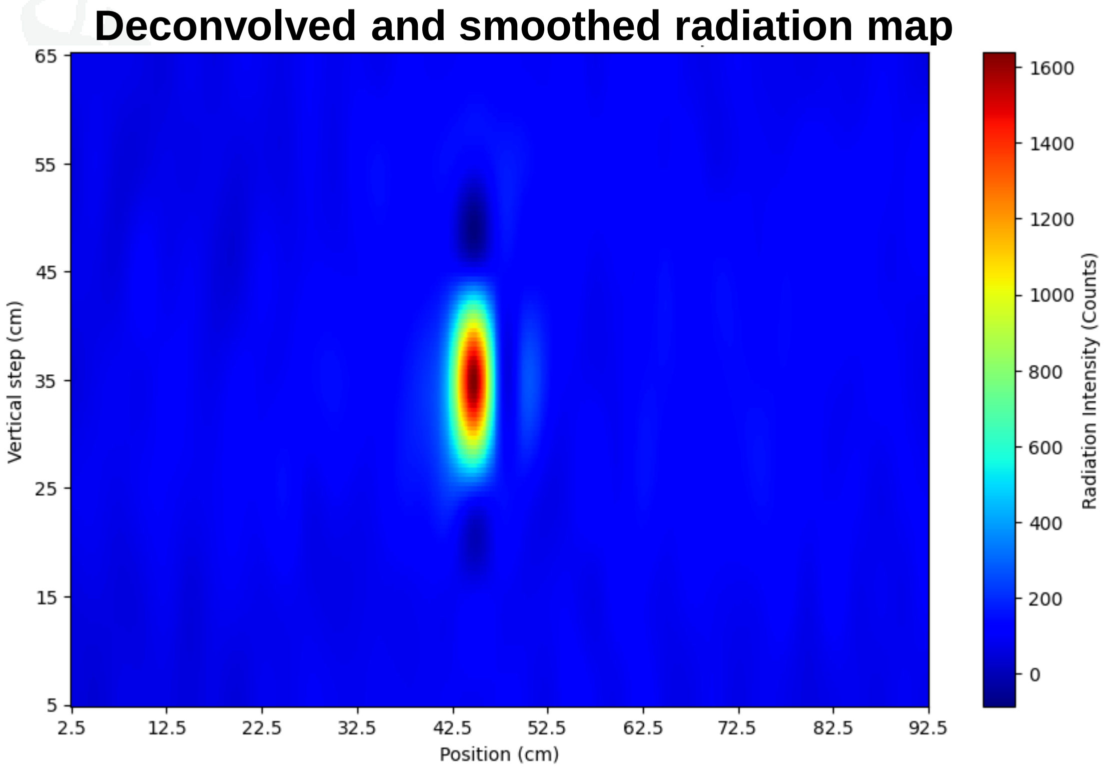


$$p(x, y) = \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} x^i y^j$$

Abdullah, D., Fajriana, F., Maryana, M., Rosnita, L., Utama Siahaan, A. P., Rahim, R., & Hadikurniawati, W. (2018, November). Application of interpolation image by using bi-cubic algorithm. In *Journal of Physics: Conference*

Image processing cont'd

Preliminary Results



To measure the deviation of estimated source locations:

True source position = (47.5, 35)

Estimated source position from mapping = (44, 35)

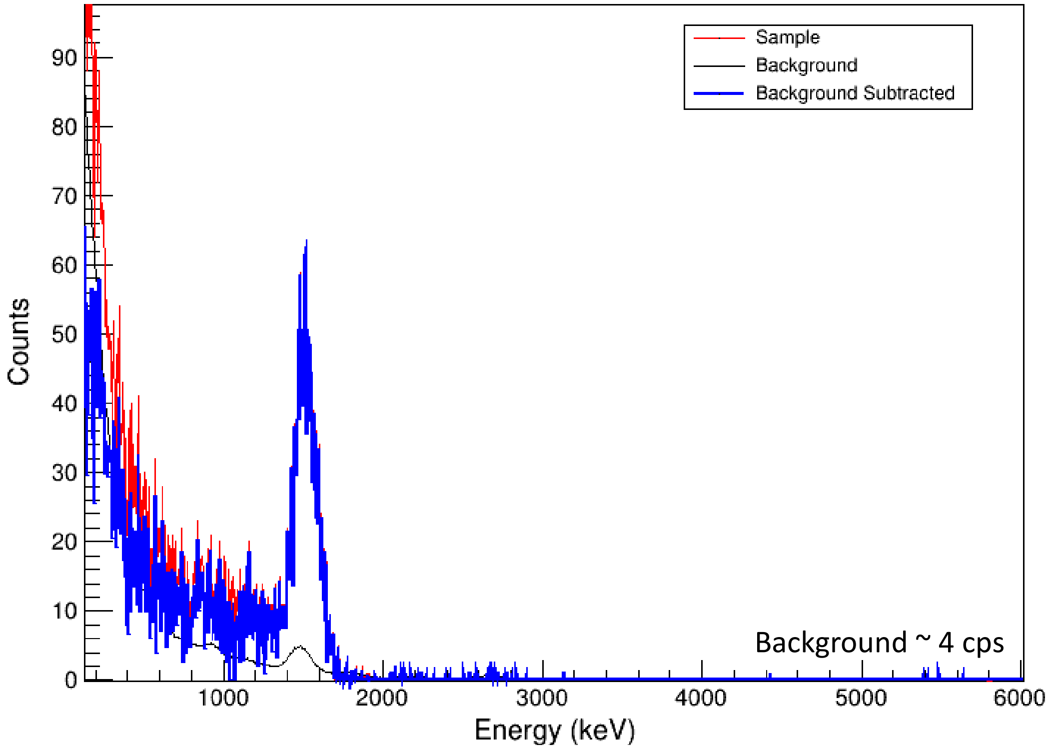
$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((xi_{estimated} - xi_{true})^2 + (yi_{estimated} - yi_{true})^2)}$$, where N is number of sources

Mean Square Root Error = 3.5 cm

Distributed sources

Preliminary Results

- The boxes were filled with potassium-rich fertiliser (white material) and sand (brown) to create radiation hotspots.



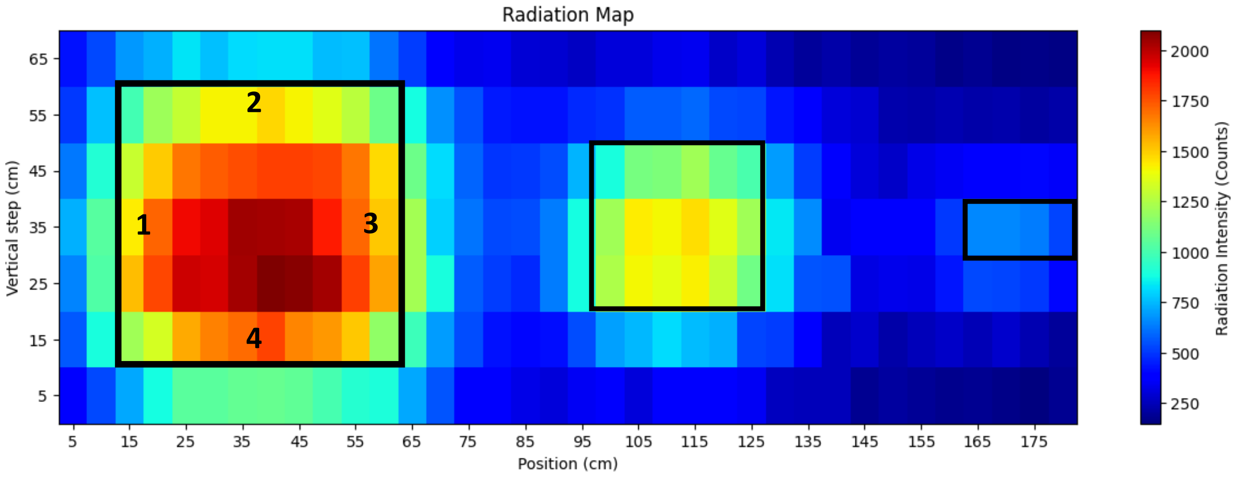
- The detector was placed a certain distance, *z*, away from the wall.

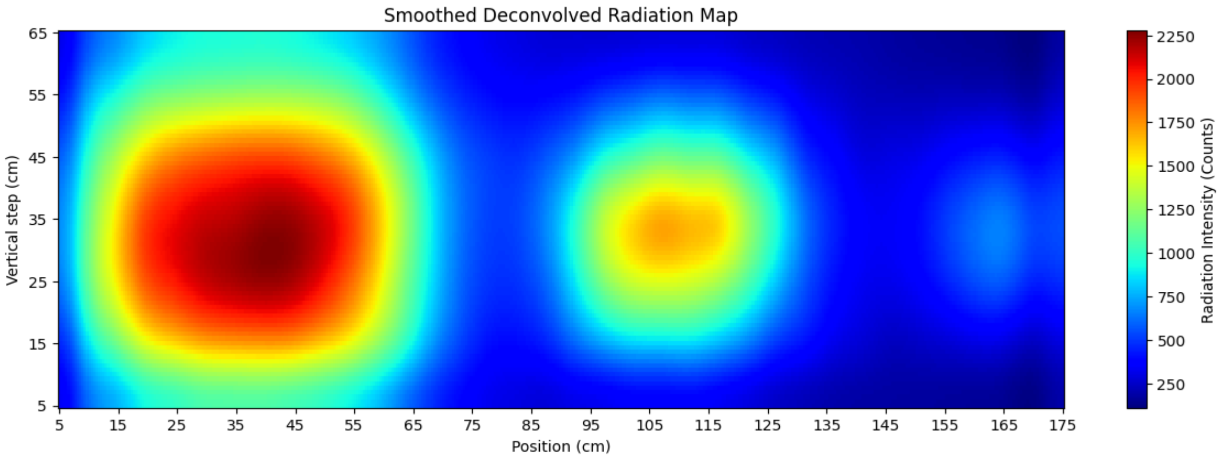
- The robot was moved in 5 cm horizontal steps and 10 cm vertical steps.

- The integral under the 1460 keV photo-peak was used to generate 2D radiation maps.

2D radiation map

Preliminary Results





$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((xi_{estimated} - xi_{true})^2 + (yi_{estimated} - yi_{true})^2)}$$

True source positions (centre)	Estimated (from deconvolved radiation map)
1. (15, 35)	(15, 32)
2. (35, 55)	(37, 49)
3. (55, 35)	(57, 32)
4. (35, 15)	(37, 17)

$$\text{RMSE} = \sqrt{\frac{1}{4}\,(0+9+4+36+4+9+4+4)}$$

$$= \sqrt{17.5}$$

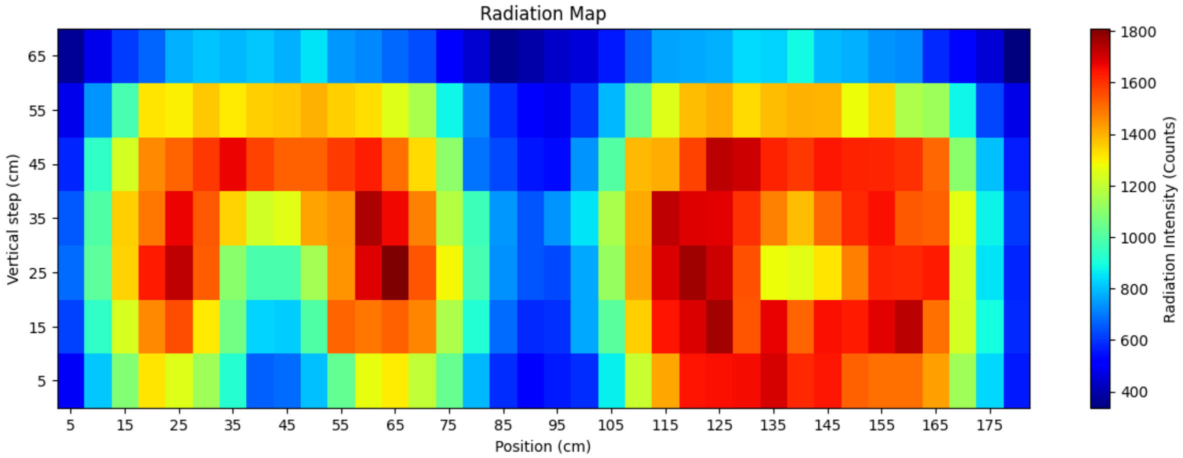
$$= 4.18 \text{ cm}$$

The estimated position deviates from the true source location by **4.18 cm**

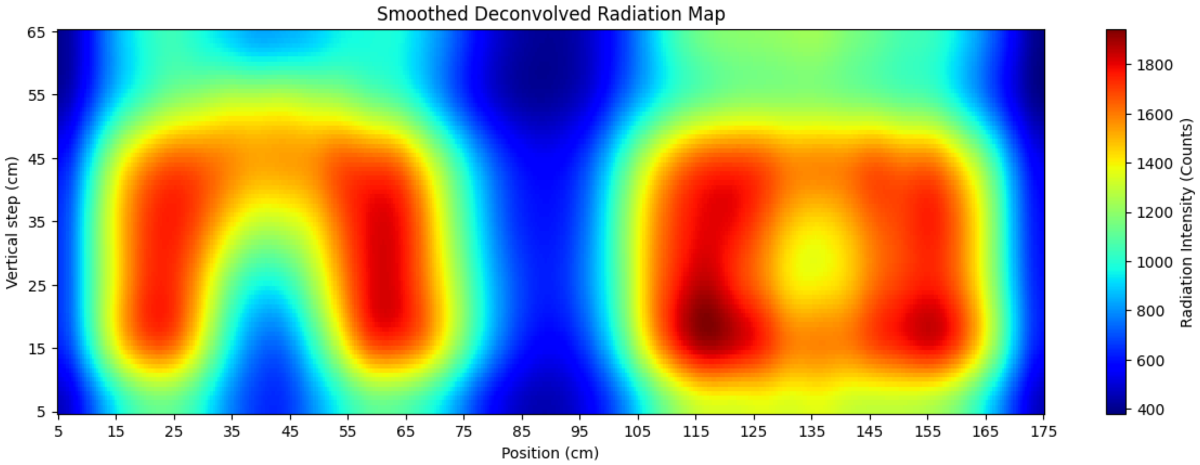
Conclusions

Preliminary Results

Ground truth



2D radiation map with no filter/ algorithm applied



Richardson-Lucy algorithm + bi-cubic interpolation

Mean Square Root Error = 5.71 cm

- The mapping gives a sense of the distribution of the source.
- Current algorithms underestimate the source locations.

Future Work

- Refine and apply image processing algorithms to create more accurate radiation maps.
- Test various scanning patterns to optimise scanning time.
- Explore advanced data analysis techniques, such as machine learning.

THANK YOU…

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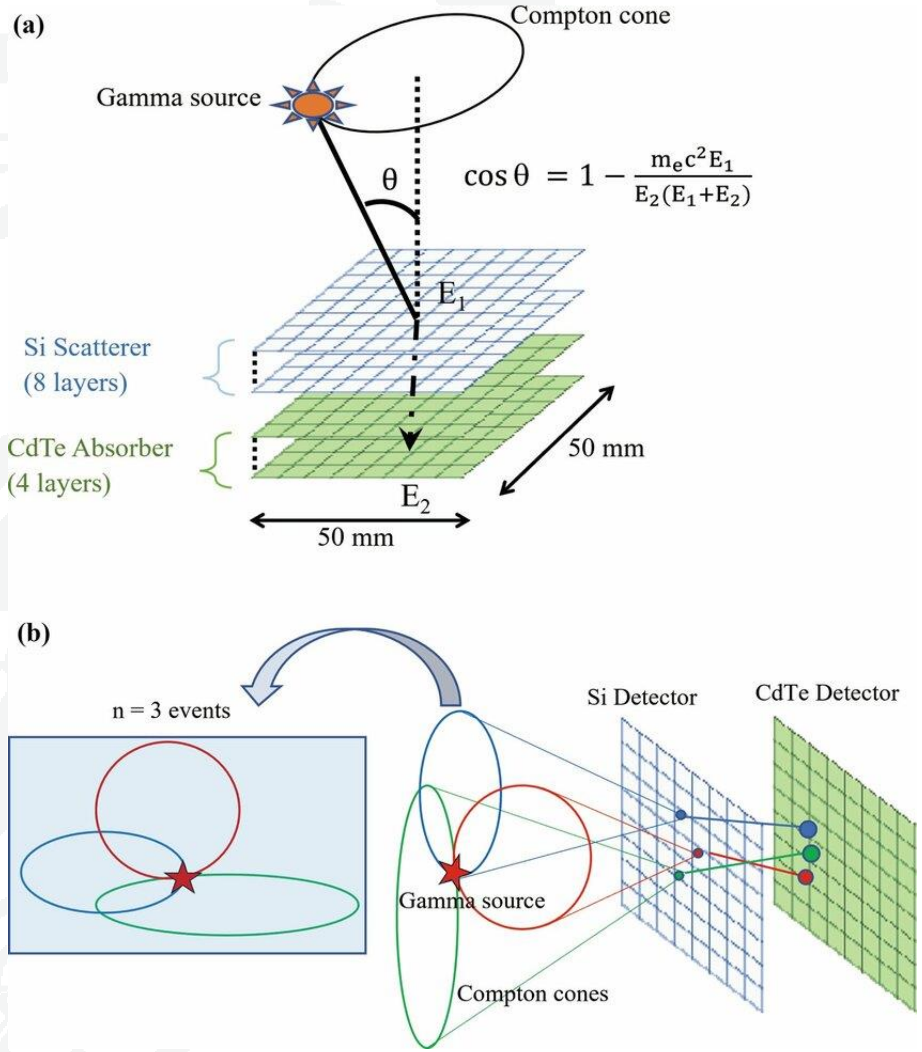
- *Dr Pankaj Joshi*
- *Dr Mark Post*
- *Dr Julien Bordes*
- *Dr Oscar Kureba*
- *Jonathan Procter*
- *Mike Angus*
- *Tim Ayers*
- *Bob Hide*

Back up slides

Techniques for source localisation

1. Compton cameras



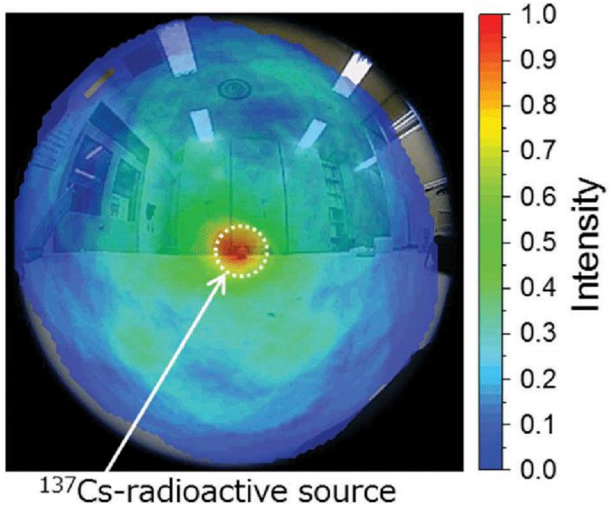


Fig.6. Reconstructed radiation image of a ^{137}Cs radioactive point source obtained using a compact Compton camera.

Algorithms used

- Simple back-projection (SBP)
- Filtered back-projection (FBP)
- Maximum Likelihood Expectation Maximization (MLEM)

Fig. Schematic illustration of a general Compton camera (**a**); Compton cones of each event are superimposed to locate the γ-ray source (**b**).

1. Parajuli, R. K., Sakai, M., Arakawa, K., Kubota, Y., Kubo, N., & Tashiro, M. (2021). Carbon range verification with 718 keV Compton imaging. *Scientific Reports*, *11*(1), 21696.
2. Sato, Y., Terasaka, Y., Utsugi, W., Kikuchi, H., Kiyooka, H., & Torii, T. (2019). Radiation imaging using a compact Compton camera mounted on a crawler robot inside reactor buildings of Fukushima Daiichi Nuclear Power Station. *Journal of Nuclear Science and Technology*, *56*(9-10), 801-808..

Techniques for source localisation contd..

2. Multiple detector systems

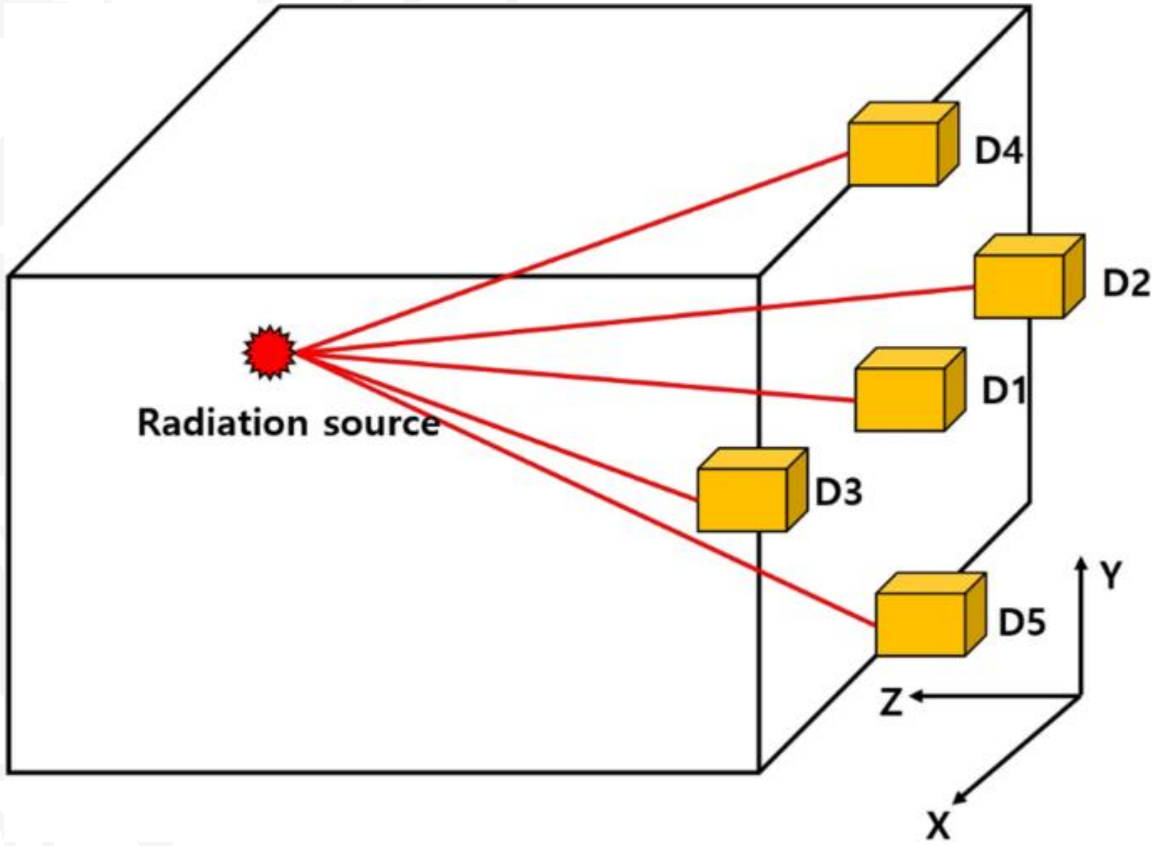


Fig. Schematic diagram of the radiation source position tracking system using multiple radiation spectroscopy detectors

Methods used

- Triangulation

The radiation intensity is inversely proportional to the square of the distance

Lee, S. J., & Baek, C. H. (2022). Radiation source position tracking system using multiple radiation spectroscopy detectors. *Journal of the Korean Physical Society*, *81*(1), 18-23.

Techniques for source localisation contd..

3. Mobile platforms e.g. radiation detectors mounted on autonomous robots, cars and drones.

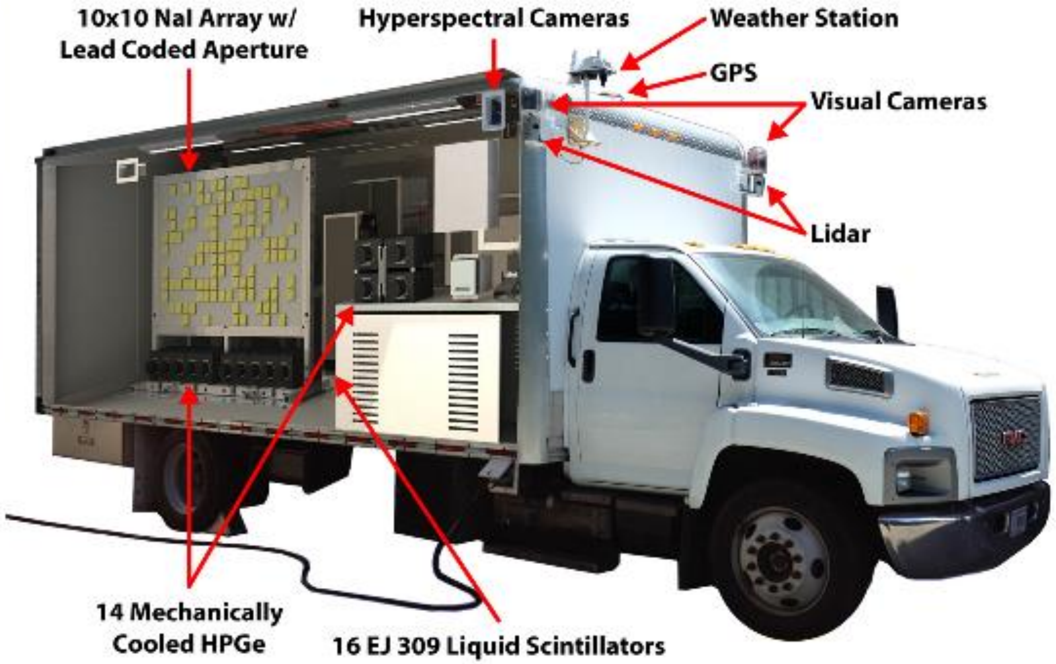


Fig. Drone used for monitoring, mapping, and source localization purposes (a); Radiological multi-sensor analysis platform (RadMap) system carried by a truck (b).

Marques, L., Vale, A., & Vaz, P. (2021). State-of-the-art mobile radiation detection systems for different scenarios. *Sensors*, *21*(4), 1051.

Choice of detector

Bismuth Germanate (BGO) detector

- Coupled a BGO crystal to Silicon Photomultipliers (SiPMs) from Hamamatsu (MPPC S14160/S14161 series).
- Has an energy resolution of 10 - 12% at 662 keV

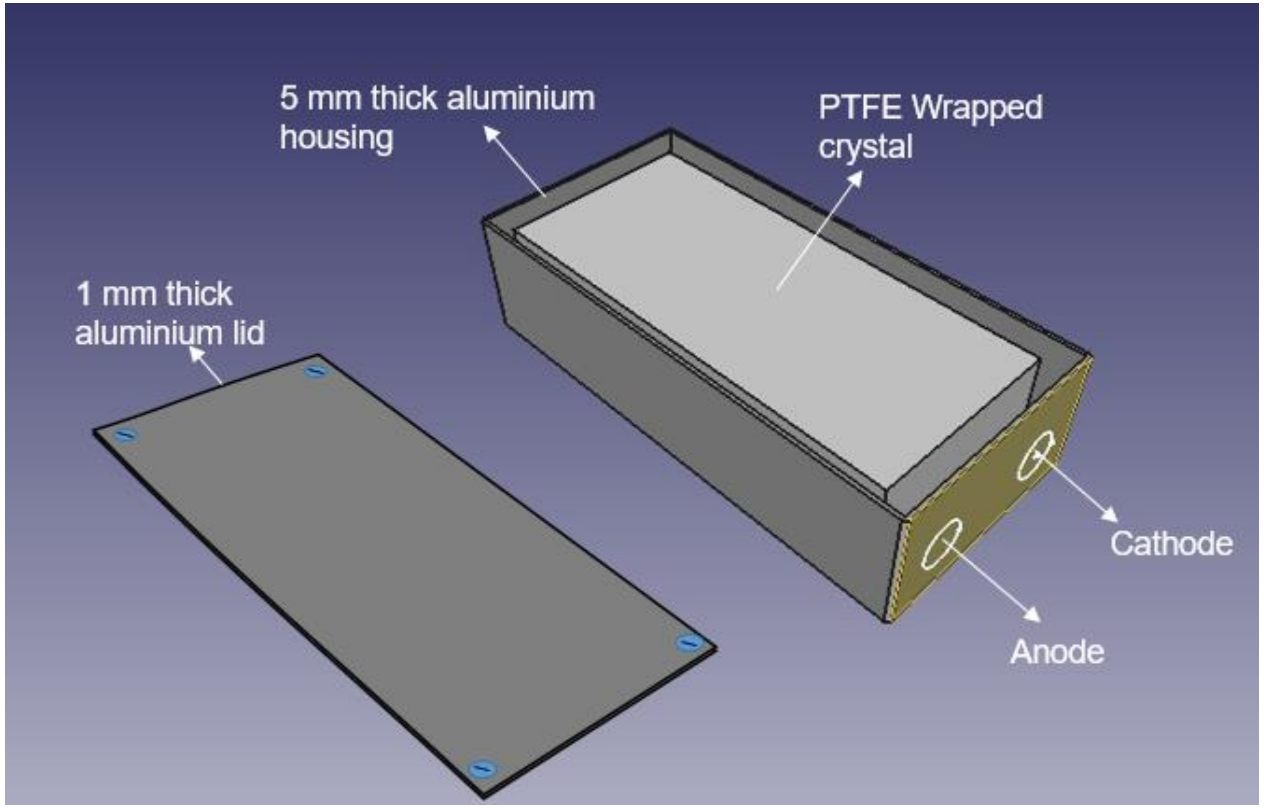
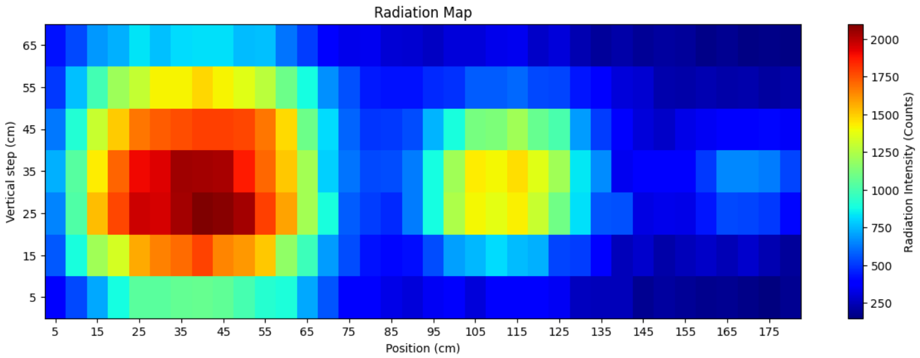
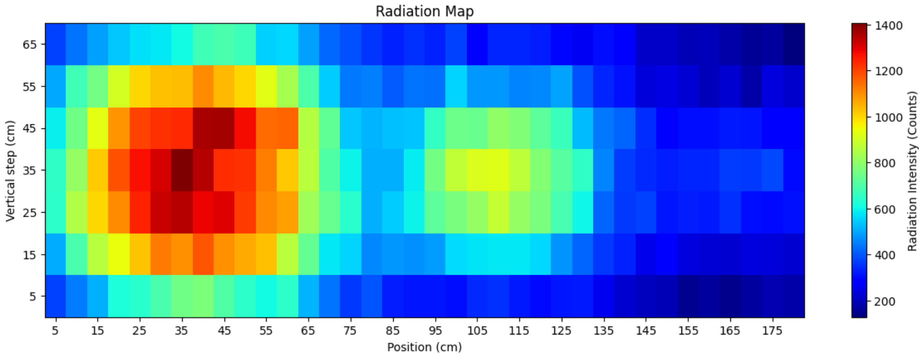


Fig. Computer Aided Design of a 2cm thick Bismuth Germanate (BGO) scintillation detector housed in an aluminium casing.

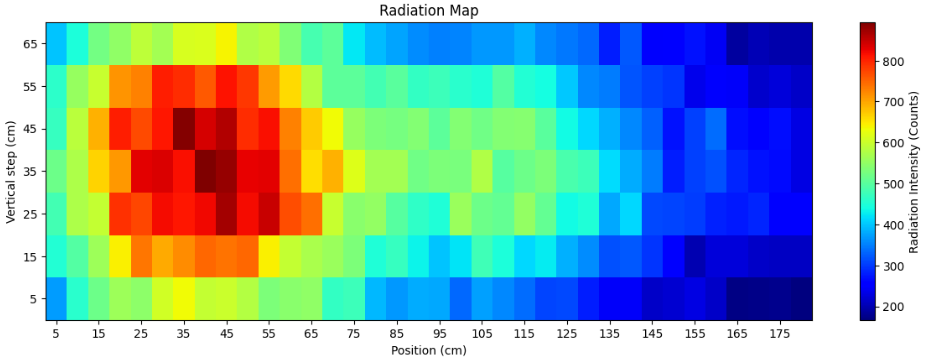
Effects of varying the source-detector distance



Detector
placed 5 cm away



Detector
placed 10 cm away



Detector
placed 20 cm away

Ways of quantify blurring effect?

- **Variance of Laplacian** - Measures the focus level by detecting edge sharpness via the Laplacian operator. A lower variance indicates less defined edges, which means the image is likely blurrier.

- **Fourier Transform Analysis** - Examine the distribution of high frequencies. Blur reduces high frequencies, so the absence of these frequencies can indicate blurring.

Image processing techniques

Deconvolution is a post-processing step that makes images appear “sharper,” or more in focus. It is a mathematical image processing technique that improves the quality of an image by removing blur and enhancing contrast and resolution. Deconvolution uses an expression for the point spread function (PSF) to perform the mathematical inverse of the imaging process.

FWHM (spatial resolution) and the PSF (σ) are related as such:

$$\text{FWHM} = 2\sqrt{2\ ln2\ \sigma}$$

The Richardson-Lucy algorithm is based on the Bayesian maximum likelihood estimation assuming a Poisson noise model. The iterative formula is:

$$f_{k+1}(x,y) = f_k(x,y) \cdot \left[\frac{g(x,y)}{(fk*\mathrm{h})(x,y)} * h*(x,y)\right]$$

Where: $f_k(x,y)$ is the estimated (sharp) image at iteration k

$g(x,y)$ is the observed (blurred) image.

$h(x,y)$ is the point spread function (PSF) (i.e., the known blur kernel).

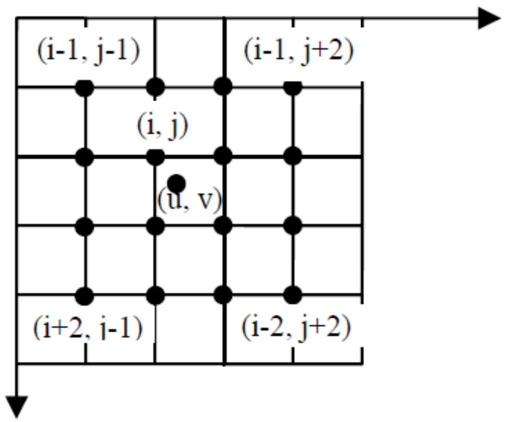
$h*(x,y)$ is the flip-conjugate of the PSF.

$*$ represents the convolution operation.

Image processing techniques

Bi-cubic interpolation was used to smoothen the radiation maps. It estimates the colour or intensity of new pixels based on a weighted average of neighbouring pixels, resulting in a smoother and more accurate representation of the image. This method employs cubic polynomials to interpolate between 16 pixels around the target pixel. Here’s a breakdown of the main steps involved:

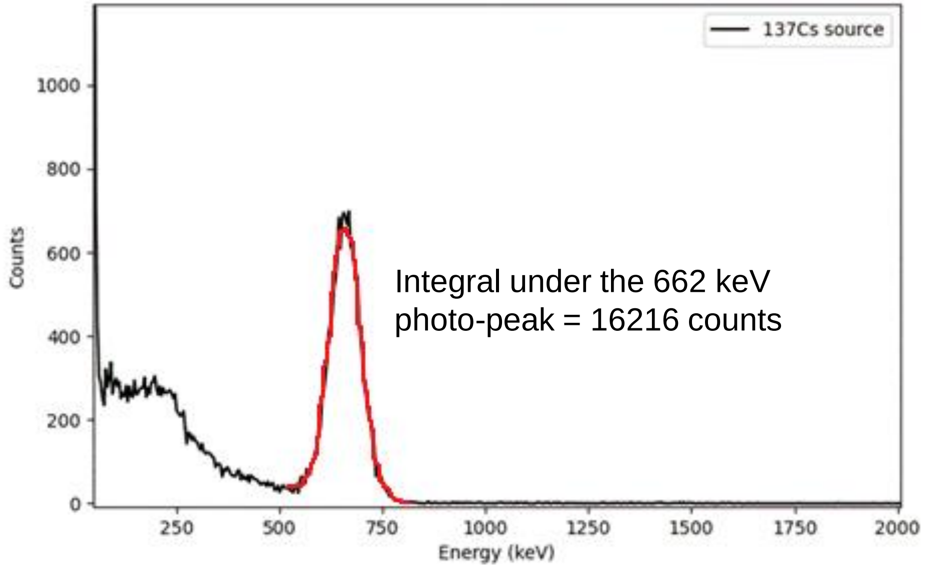
- **Grid Selection** – Bi-cubic interpolation first identifies the nearest 4×4 grid of pixels surrounding the point that needs interpolation.
- **Polynomial Calculation** – It calculates the cubic polynomials that best fit the pixel values in the grid.
- **Value Estimation** – The interpolation function uses these polynomials to estimate the pixel intensity values at the target position.

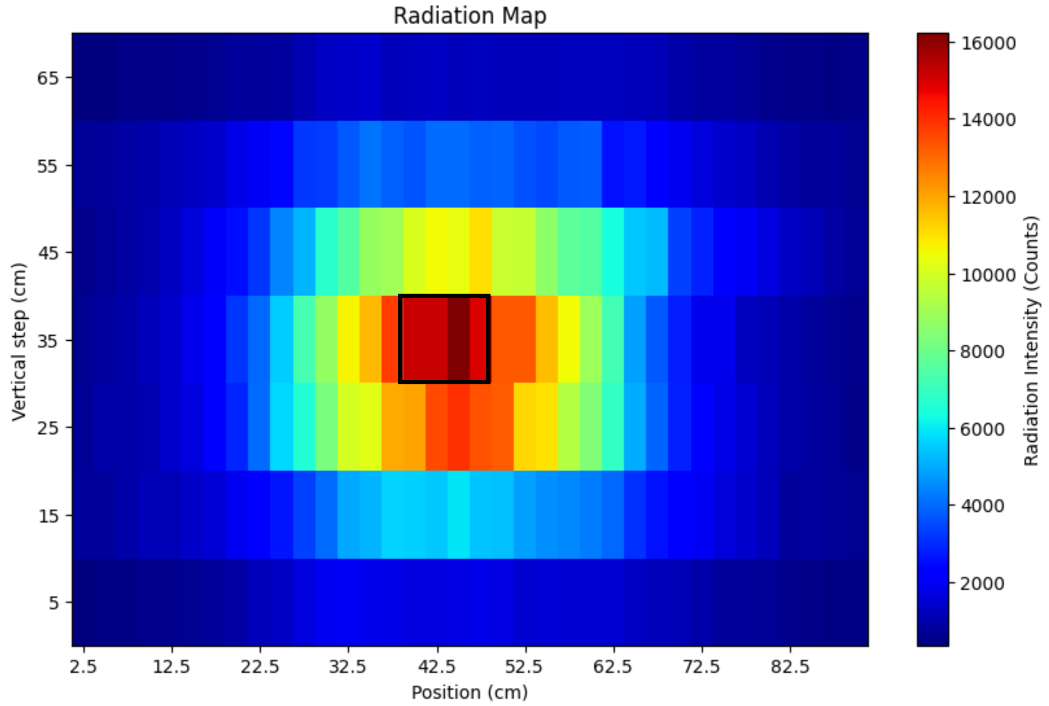


Point Spread Function (PSF) –uncollimated source

Preliminary Results

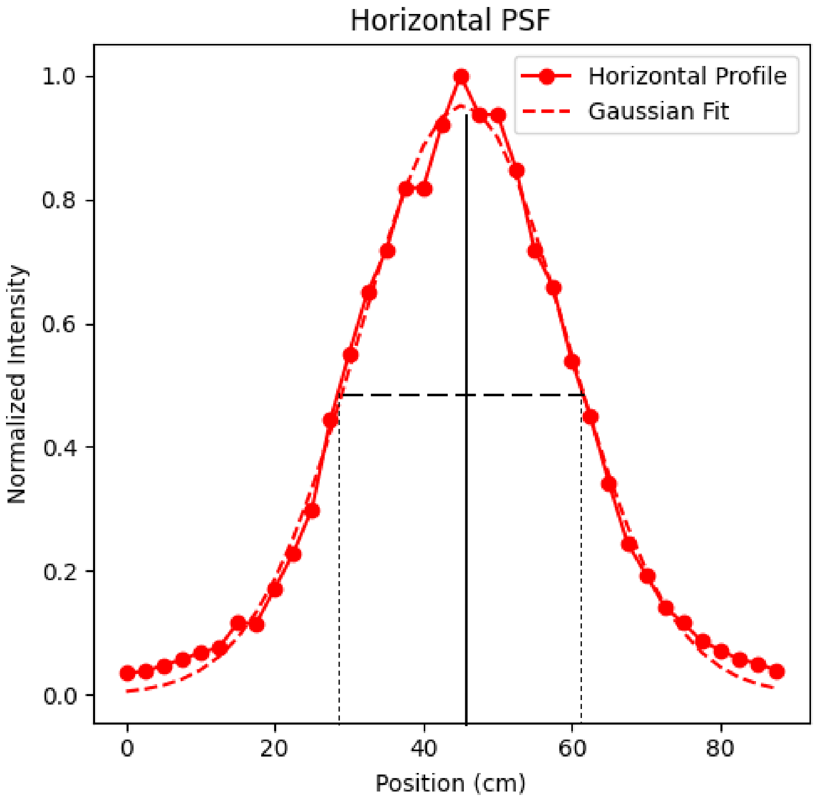
- A ^{137}Cs source was used to determine the Point Spread Function.
- The detector was placed 10 cm away from the wall and moved in 2.5 cm horizontal steps and 10 cm vertical steps.
- A 2D radiation map was generated by overlaying the radiation data after background subtraction with the position data of the detector.

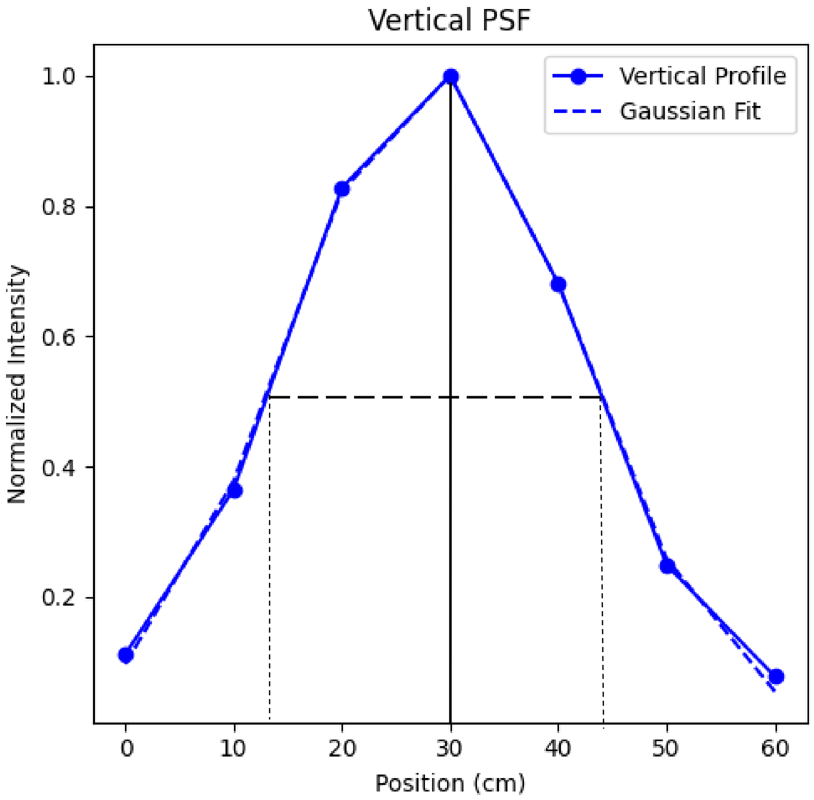




Point Spread Function (PSF) cont'd

Preliminary Results





$$\text{FWHM} = 2\sqrt{2\, ln2\ \sigma} \approx 2.355\sigma$$

where σ is the standard deviation obtained from the Gaussian fit.

FWHM_x (Horizontal Resolution) = 33.01 cm

FWHM_y (Vertical Resolution) = 30.88 cm

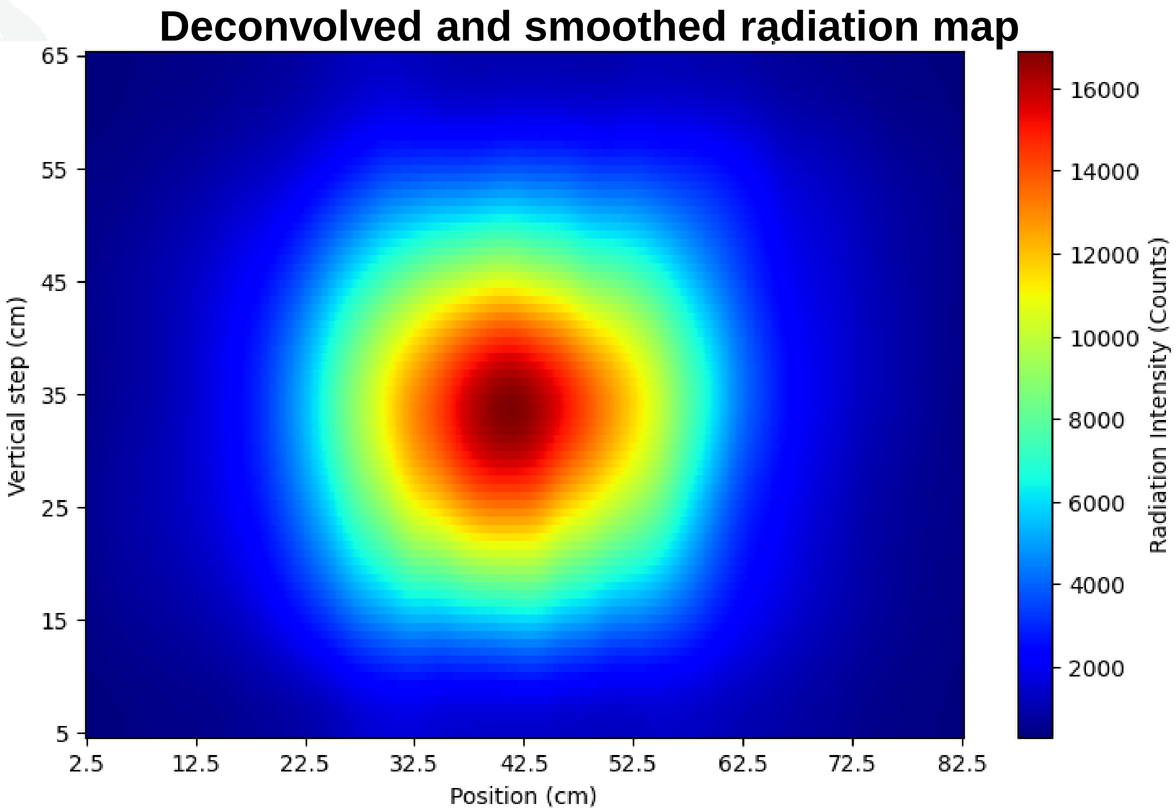
Spatial resolution = $\sqrt{(FWHMx)2 + (FWHMy)2}$

Spatial resolution = 45.2 cm

σ = 19.2 cm

Image processing of un-collimated source

Preliminary Results



$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((xi_{estimated} - xi_{true})^2 + (yi_{estimated} - yi_{true})^2)}$$

True source position = (47.5, 35)
Estimated source position from mapping = (42.5, 33)
Mean Square Root Error = 5.40 cm

- The mapping deviates from the true source location by **5.40 cm**