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Novel Approaches to Radiation Detection

Ren Cooper
Lawrence Berkeley National Laboratory

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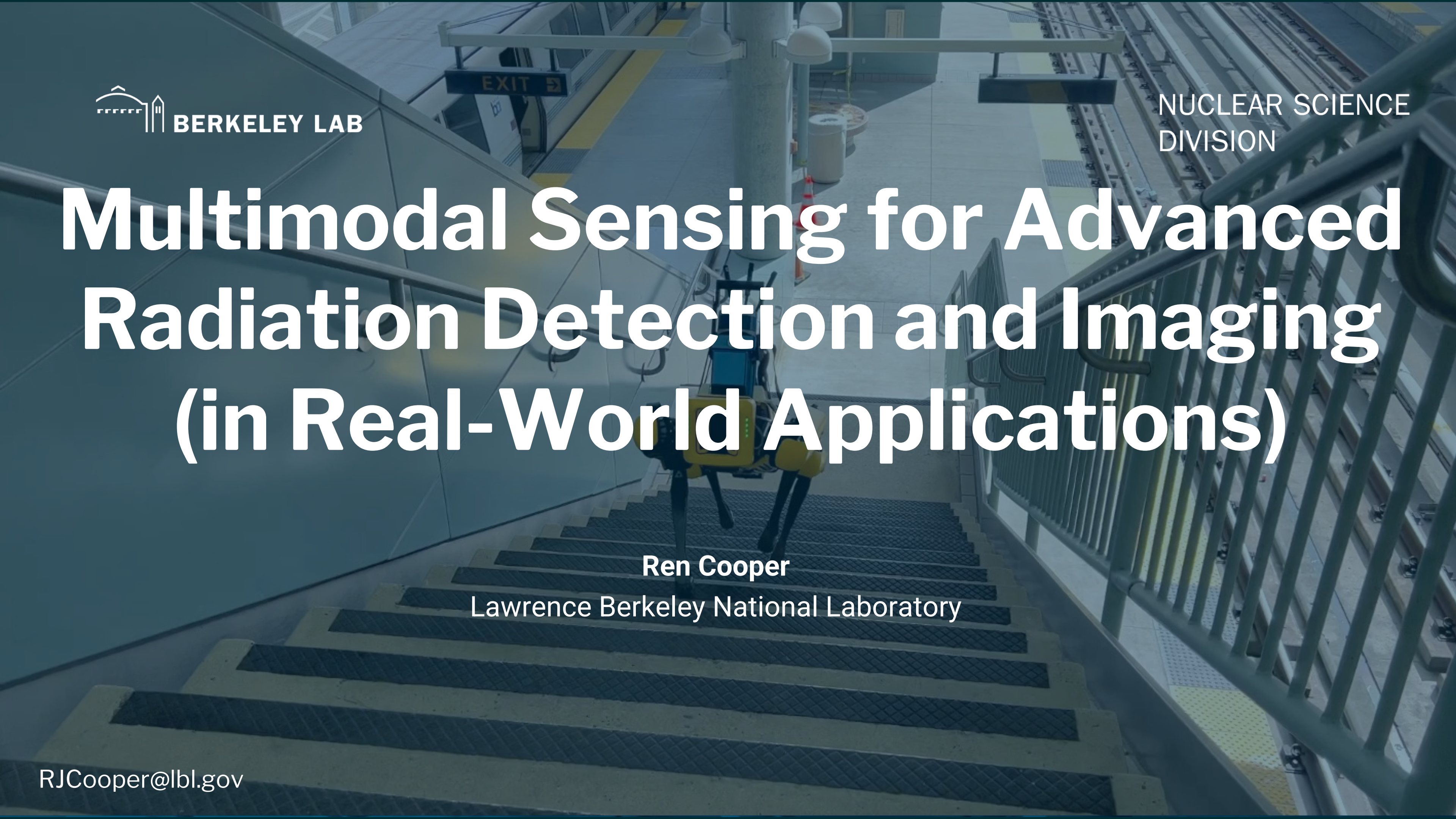

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Multimodal Sensing for Advanced Radiation Detection and Imaging (in Real-World Applications)

Ren Cooper
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Applications Relevant To This Talk

Broadly speaking, nuclear safety and nuclear security

Radiological/Nuclear Search

A tiny but dangerous radioactive capsule is found in Western Australia

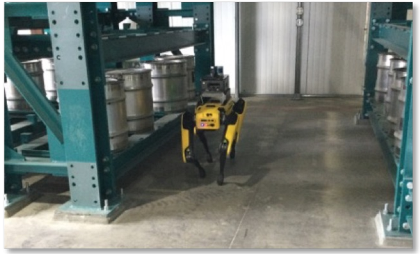
UPDATED FEBRUARY 1, 2023 · 7:34 AM ET

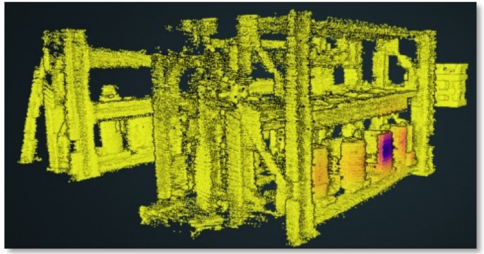
By Joe Hernandez

In this photo provided by the Department of Fire and Emergency Services, its members search for a radioactive capsule believed to have fallen off a truck being transported on a freight route on the outskirts of Perth, Australia, on Saturday.

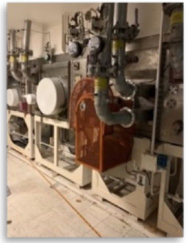
AP

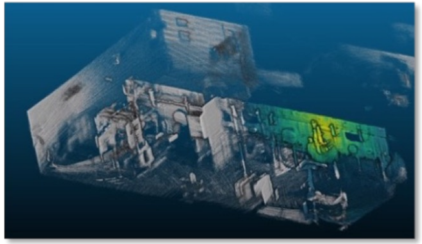
Monitoring/Decommissioning



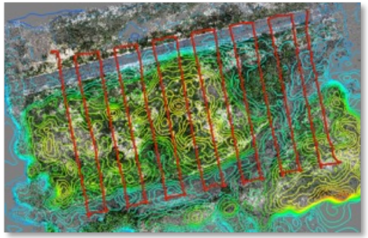


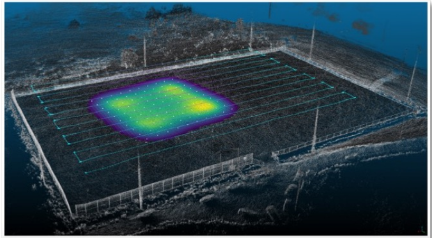
Nuclear Safeguards





Contamination Mapping



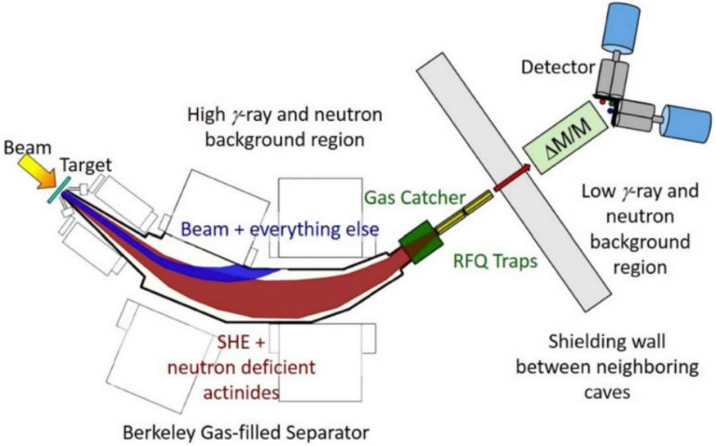


What Do I Mean by Multimodal Sensing?

- **What**: Combining data from different sensing modalities/different types of sensors

- **Why**:
  - To gain a more complete picture of a physical phenomenon or process
  - To help interpret otherwise ambiguous measurements
  - To enable new capabilities for radiation detection and imaging

Examples of Multimodal Sensing



J.M. Gates (2025), DOI: 10.1051/epjconf/201613108003

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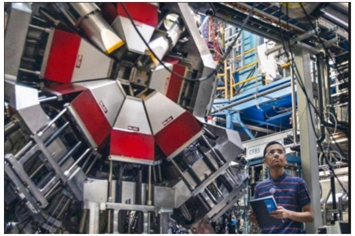
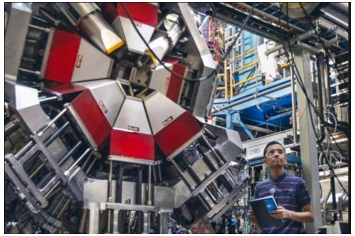
Gamma-Ray Detectors

In the lab..



Gamma-Ray Detectors

In the lab..



In the field..

The First NaI Detector - 1948

PHYSICAL REVIEW VOLUME 75, NUMBER 5 MARCH 1, 1949

The Detection of Gamma-Rays with Thallium-Activated Sodium Iodide Crystals*

ROBERT HOFSTADTER
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received September 27, 1948)

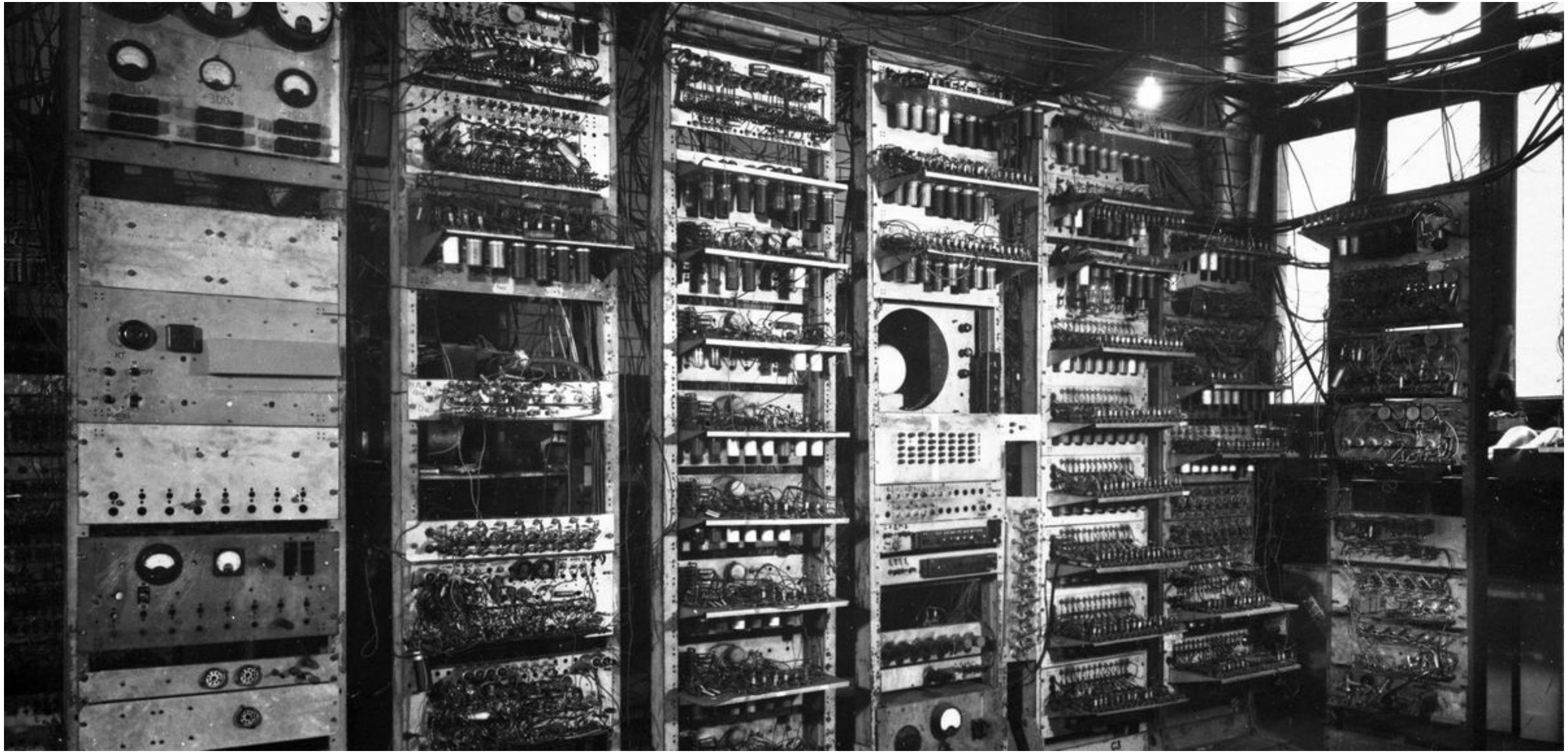
Thallium-activated sodium iodide crystals may be used as efficient detectors of gamma-rays and other ionizing radiations. The crystals are used in combination with a photo-multiplier after the manner of Kallmann. Curves are given which show the duration of the light emission process, the distribution of light pulse sizes, the energy discrimination possibilities, and the dependence of number of counting events on photo-multiplier voltage and amplifier gain. Comparison curves are shown for NaI(Tl) and anthracene. A description is given of the method of preparation of polycrystalline samples and single crystal specimens of the sodium iodide-thallium phosphor. A few remarks are made concerning the combination of alkali halide phosphor crystals with photographic plates.

I. INTRODUCTION

THE detection of beta-particles and gamma-rays by the combination of a luminescent crystal (phosphor) and a photo-multiplier vacuum tube has been successfully demonstrated by many investigators.[1–6] The earliest work in which large crystalline samples were used was performed by H. Kallmann.[1] Kallmann showed that large clear pieces of napththalene produced measurable scintillations when exposed to

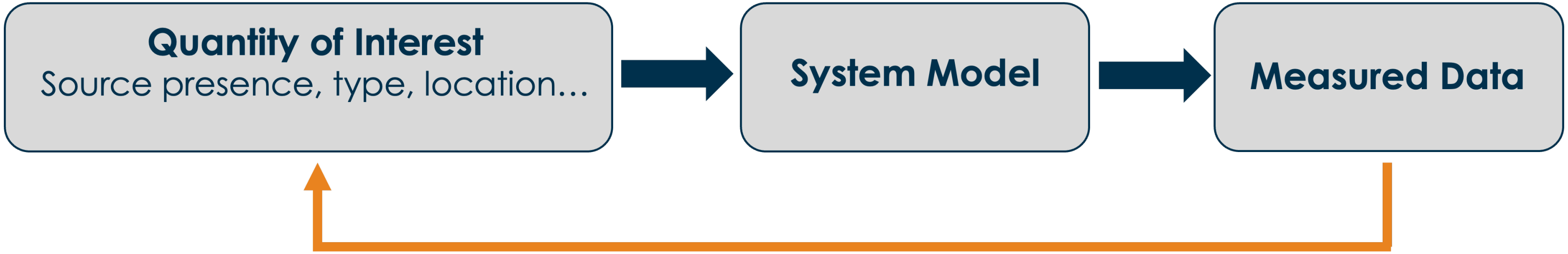
Amplified noise pulses are, unfortunately, not small compared with light flashes in naphthalene, calcium tungstate, and anthracene. Consequently, there are important advantages in cooling the photo-multiplier tube to low temperatures at which the frequency of occurrence of noise pulses becomes insignificant compared with the signal. On the other hand, the experimental difficulties in cooling the tube may prove to be a disadvantage in some experiments.

Computing in 1948…



Multimodal Sensing for Radiation Detection

- 'Contextual information' can help solve radiological/nuclear inverse problems such as anomaly detection, imaging, and mapping



Multimodal Sensing for Radiation Detection

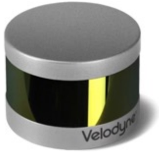
- ‘Contextual information’ can help solve radiological/nuclear inverse problems such as anomaly detection, imaging, and mapping

Quantity of Interest
Source presence, type, location…

→ **System Model** → **Measured Data**

Video

Lidar



Contextual information provides inputs, constraints, or priors to the ‘system model’

e.g., detector locations, environmental constraints

Meteorological

GPS/Inertial

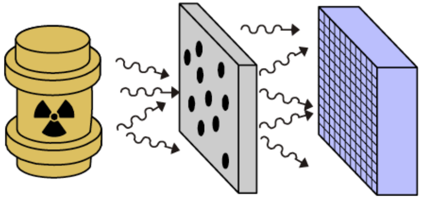
Conventional Gamma-Ray Imaging

Radiation Survey: Map the count rate/activity at each *measurement location*

Radiation Imaging: Reconstruct where the activity is *coming from*

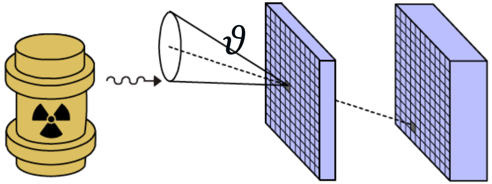
Coded Aperture Imaging

("Low" Energy)



Compton Imaging

(>"Low" Energy)

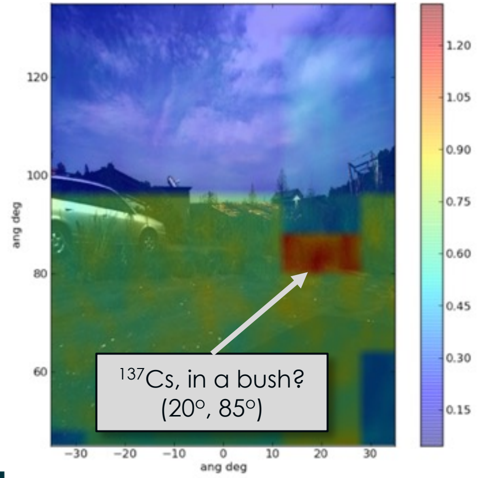


$$\cos\vartheta = 1 + m_0 c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_2}\right)$$

Limitations of Conventional Radiation Imaging

Conventional radiation imaging:

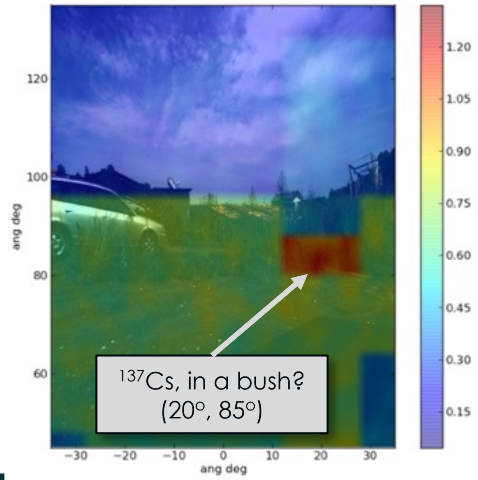
- Static system
- Fixed coordinate system
- 2D image
- Minutes to hours
- Requires an imaging system

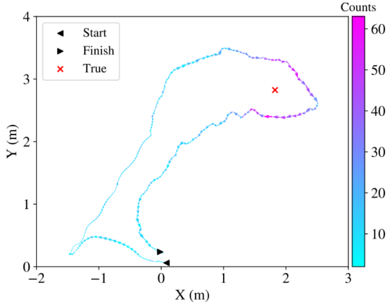


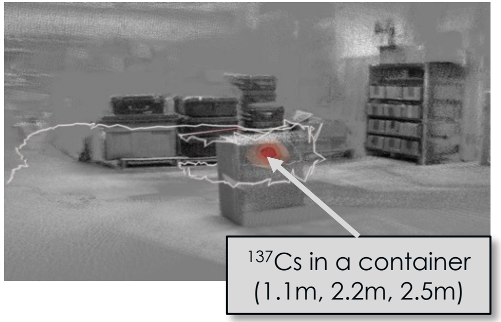
Free Moving Radiation Imaging

Conventional radiation imaging:

- Static system
- Fixed coordinate system
- 2D image
- Minutes to hours
- **Requires an imaging system**







Free moving radiation imaging:

- Overcomes $1/r^2$ limitations and increases sensitivity
- Enables 3D imaging
- **Does not require an imaging system**

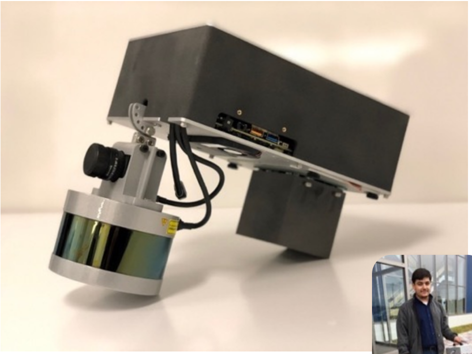
Requirements:

- Knowledge of detector response
- Continuous tracking of system pose

Radiological Scene Data Fusion (‘SDF’)

Scene Data Fusion fuses data from video/Lidar and radiation detectors to enable free moving 3D radiation imaging

Integrate Lidar, video, and INS with radiation detector <u>or</u> imager



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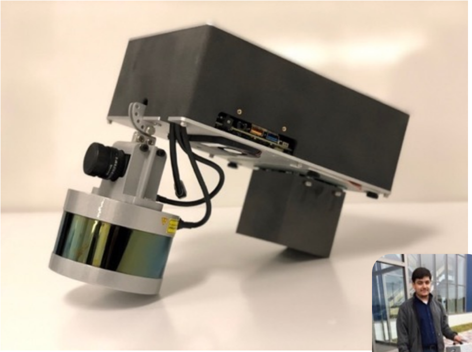
D. Hellfeld *et al.*, Sci. Rep. (2021) DOI: 10.1038/s41598-021-99588-z

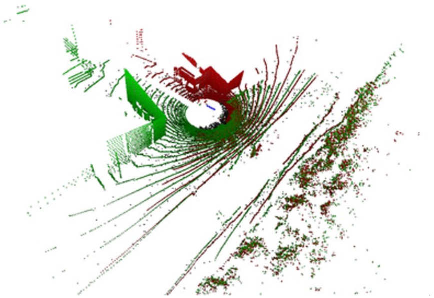
Radiological Scene Data Fusion ('SDF')

Scene Data Fusion fuses data from video/Lidar and radiation detectors to enable free moving 3D radiation imaging

Integrate Lidar, video, and INS with radiation detector <u>or</u> imager

Lidar produces a 3D map of the environment and tracks the position of the system





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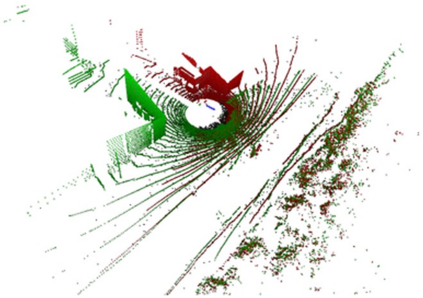
Radiological Scene Data Fusion (‘SDF’)

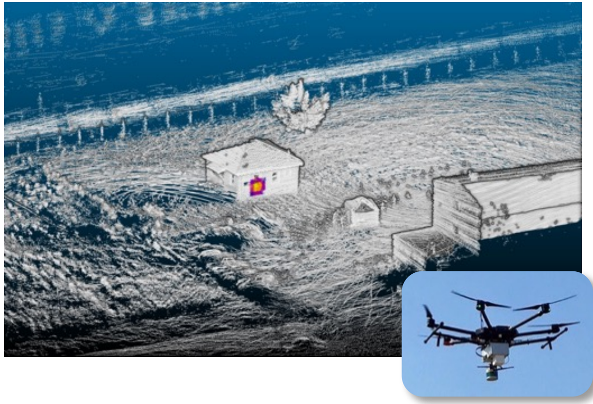
Scene Data Fusion fuses data from video/Lidar and radiation detectors to enable free moving 3D radiation imaging

Integrate Lidar, video, and INS with radiation detector or imager

Lidar produces a 3D map of the environment and tracks the position of the system

Continually fuse measured radiation data with 3D maps to enable real-time 3D imaging





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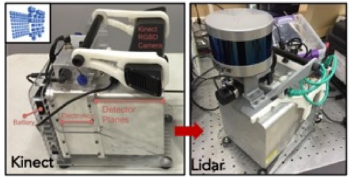
D. Hellfeld *et al.*, Sci. Rep. (2021) DOI: 10.1038/s41598-021-99588-z

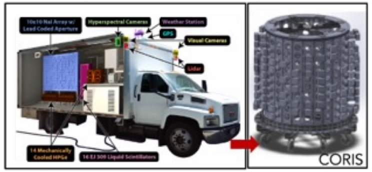
SDF Sensor Systems

HEMI (CPG-CZT)



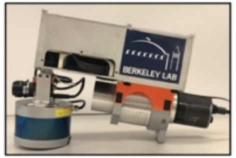
CsI-LAMP

RadMAP (NaI + HPGe + EJ309)



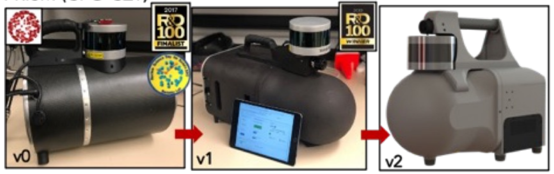
LEMURS (NaI)

LaBr-LAMP

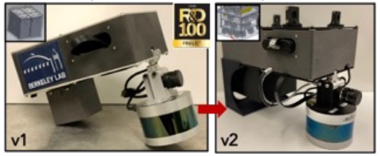


Gamma Reality Inc.

PRISM (CPG-CZT)



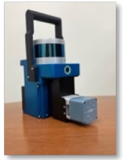
NGLAMP (CLLBC + PSD Plastic)



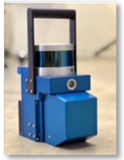
MiniLAMP (CsI)

Professor (NaI)

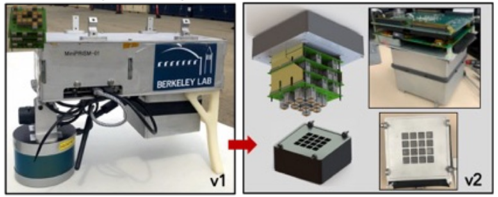
LAMP-Imager



LAMP-Mapper

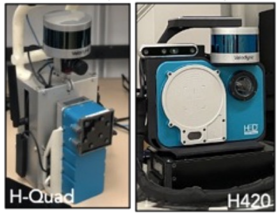


MiniPRISM (CPG-CZT)

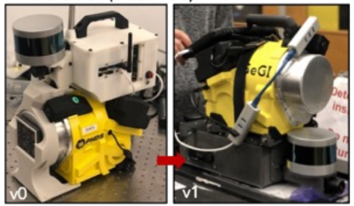


CARBS (NaI)

H3D Polaris (Pixelated CZT)

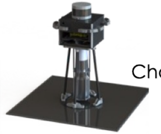


PHDs GeGI (DSSD Ge)

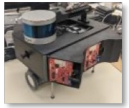


SaS4D Scanner

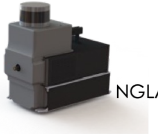
IV-LAMP



Chandelier



Radar-LAMP



NGLAMP v2

AMS Helo with ARES

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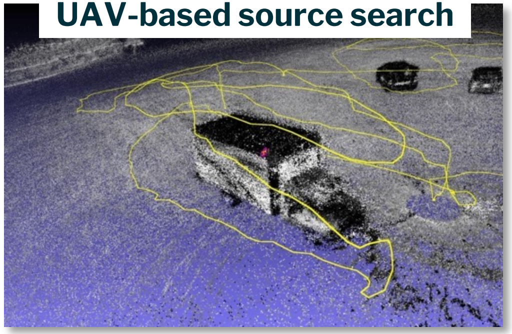
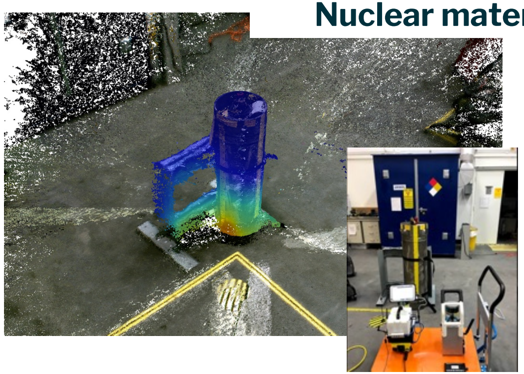
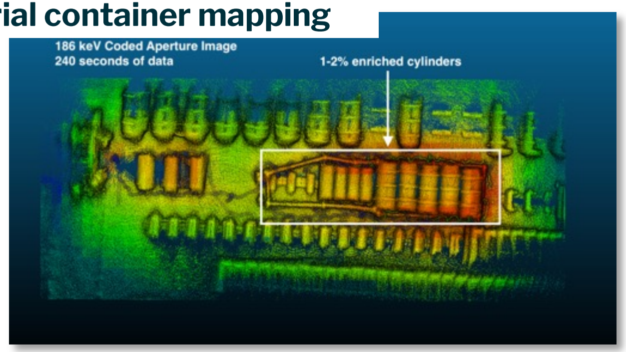
SDF Examples

UAV-based source search

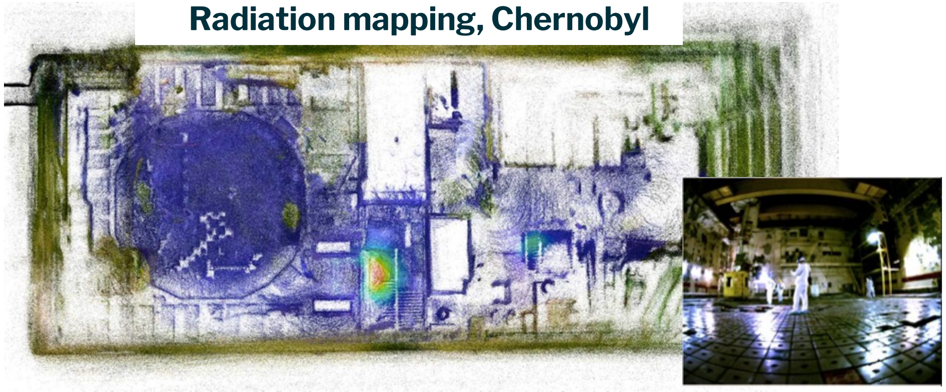


Nuclear material container mapping





Radiation mapping, Chernobyl



Cargo screening

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My Favourite SDF Result: “The Claw”

Commercial CZT Imaging system + LAMP

SDF: Robotic Integration

Gamma Reality Inc.

SDF systems are being commercialized and integrated with state-of-the-art robotic platforms

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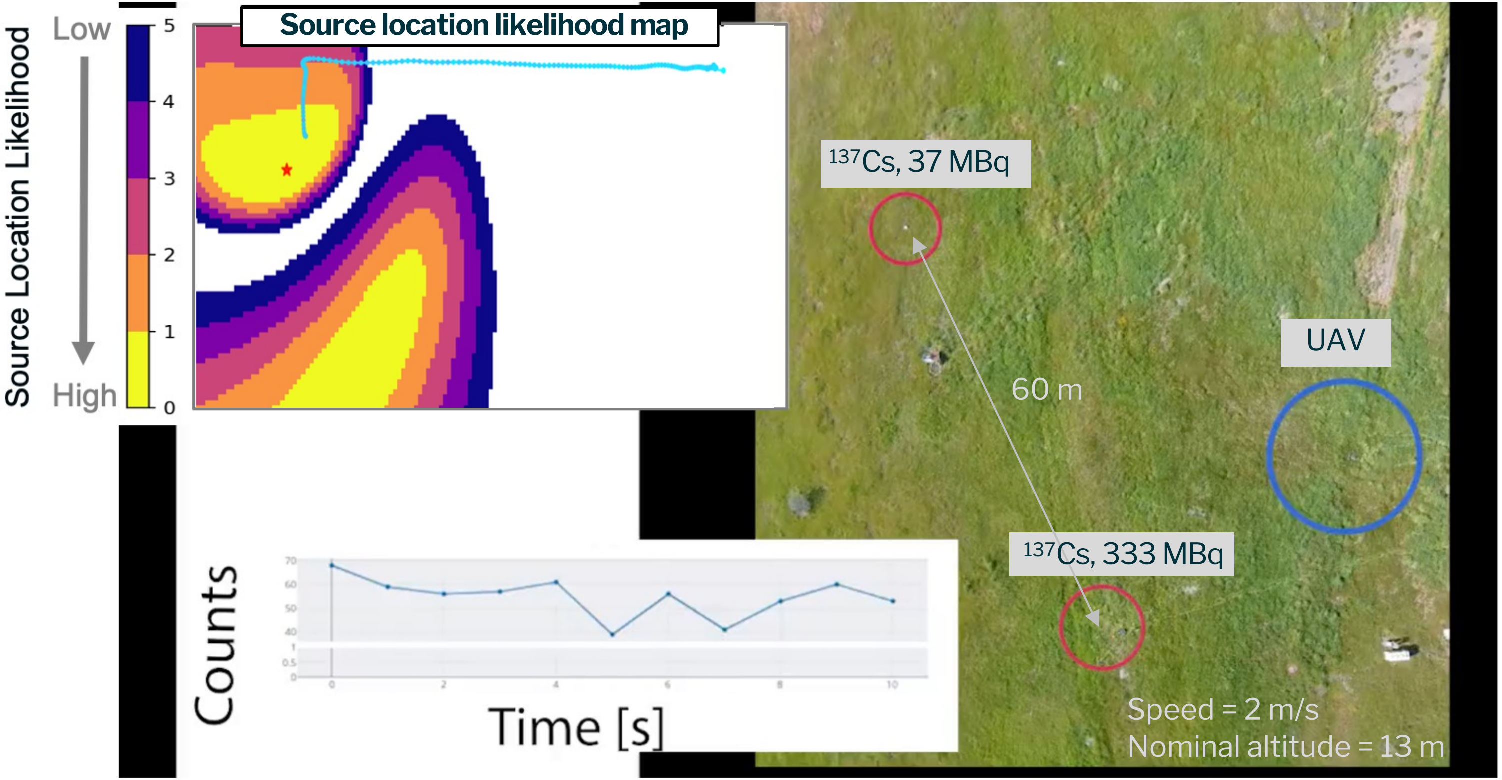
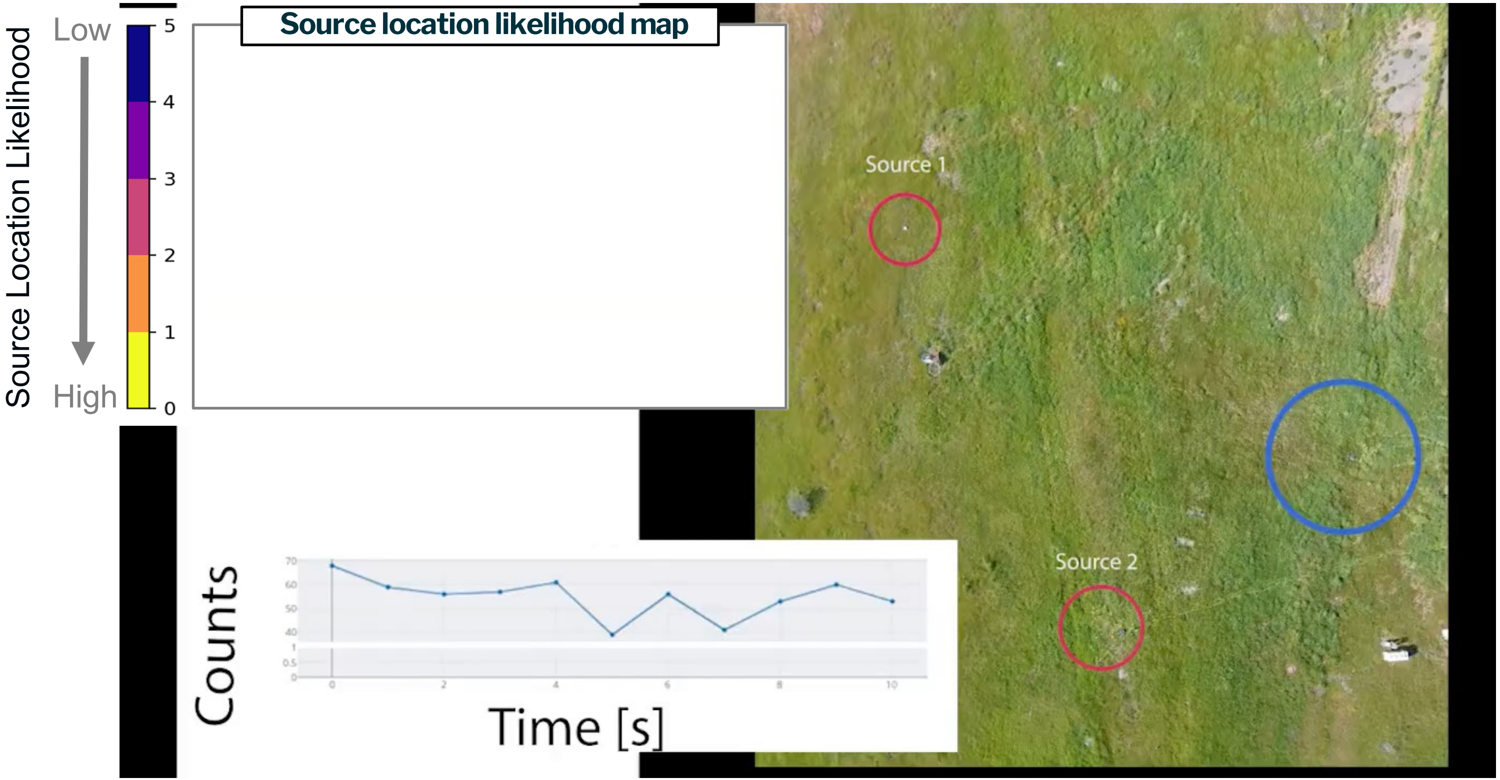
Autonomous Radiation Detection and Imaging

Removing the human from the loop: autonomous detection and localization in real-time



Autonomous Radiation Detection and Imaging

Removing the human from the loop: autonomous detection and localization in real-time



5 x speed

Autonomous Radiation Detection and Imaging

Integrating 'awareness' of radiation physics with autonomy

Autonomous Radiation Detection and Imaging

Collaborative autonomous source localization (UAV and SPOT)

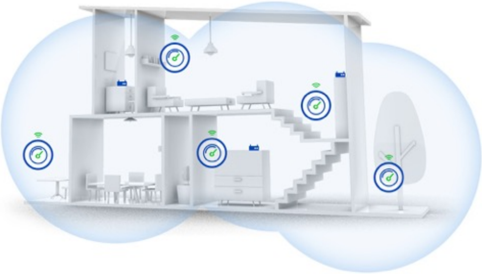
2 x speed

Networked Radiation Detection

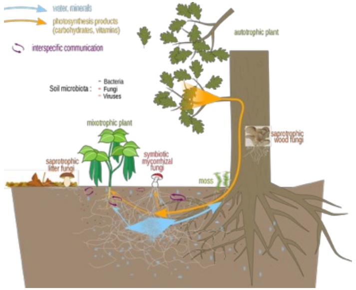
- Networks of detectors have the potential to outperform individua detectors or “arrays” of detectors
- Fusing data from multiple observations can increase the “statistical power” of a measurement
- There are many examples of adaptive sensor networks!

Smart HVAC

WiFi Mesh Networks

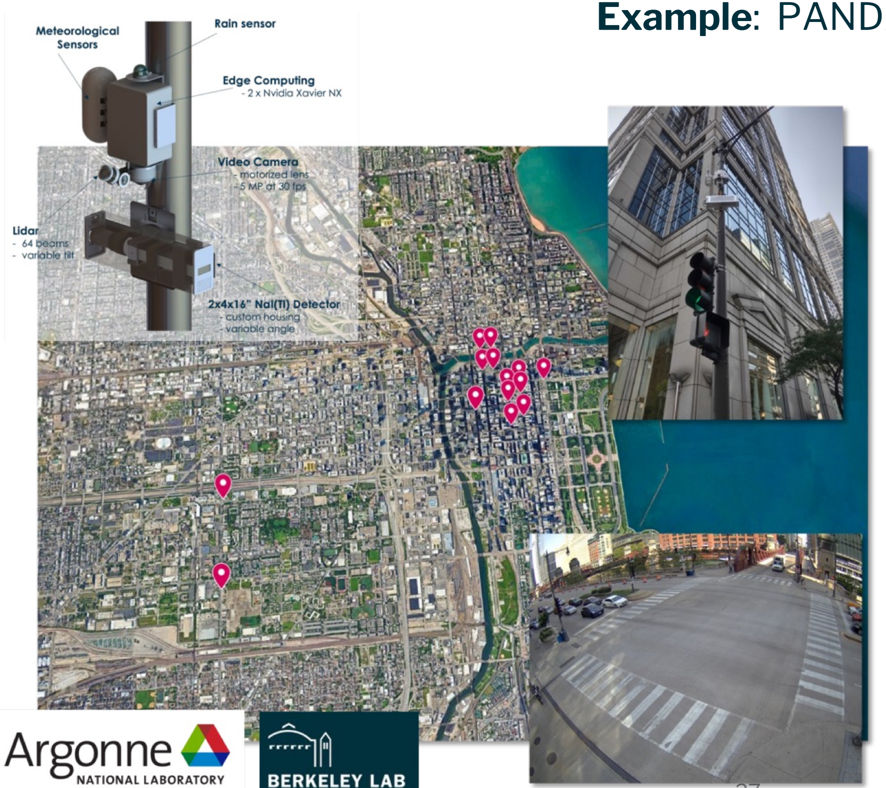


Mycorrizhal Networks
aka “Wood Wide Web”

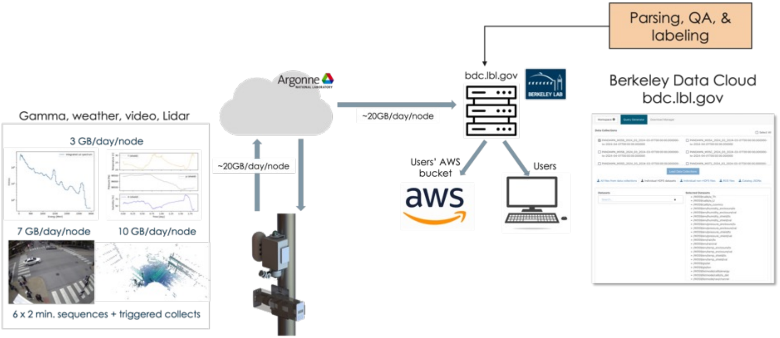


Multimodal Sensor Networks

Example: PANDAWN network in Chicago



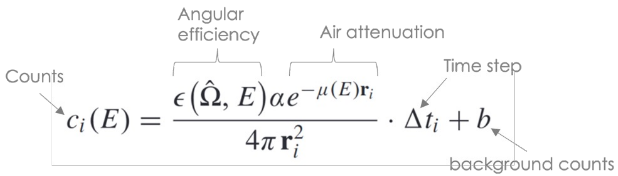
- 14+ multi-sensor nodes with integrated edge computing capabilities and real-time cloud connectivity
- **Adaptive algorithms and data acquisition**
- Automatic data labeling and curation



N. Abgrall *et al.*, (2026) DOI: 10.1109/TNS.2026.3661471

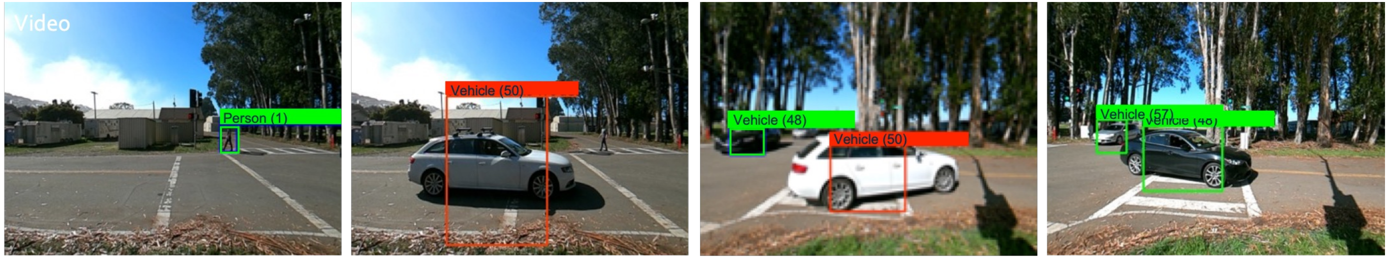
R.J. Cooper *et al.*, (2023) DOI: 10.1088/1742-6596/2586/1/012125

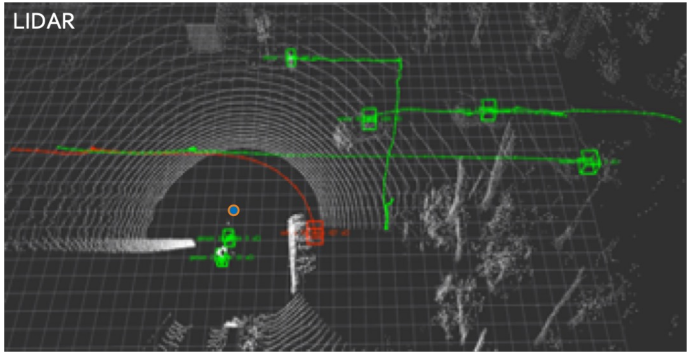
Source-Object Attribution

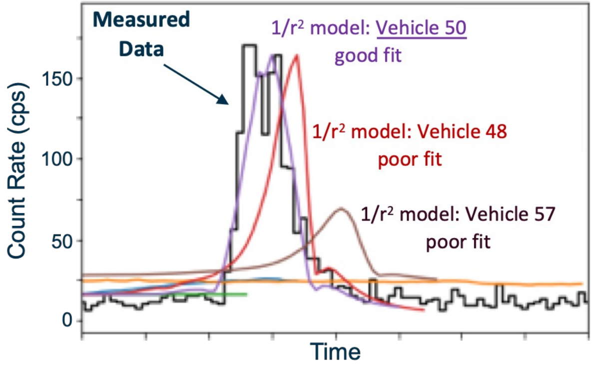


$$c_i(E) = \underbrace{\epsilon(\hat{\Omega}, E)}_{\text{Angular efficiency}} \alpha \underbrace{e^{-\mu(E)\mathbf{r}_i}}_{\text{Air attenuation}} \Big/ 4\pi \mathbf{r}_i^2 \cdot \Delta t_i + b$$

Leveraging object tracking for localization and improved detection



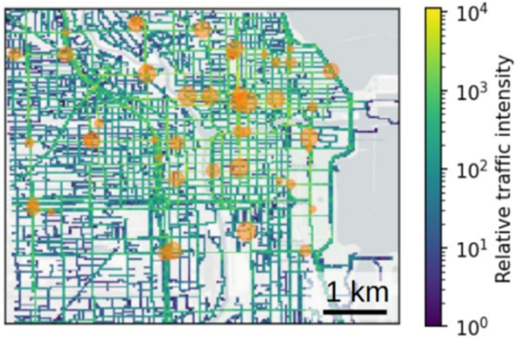


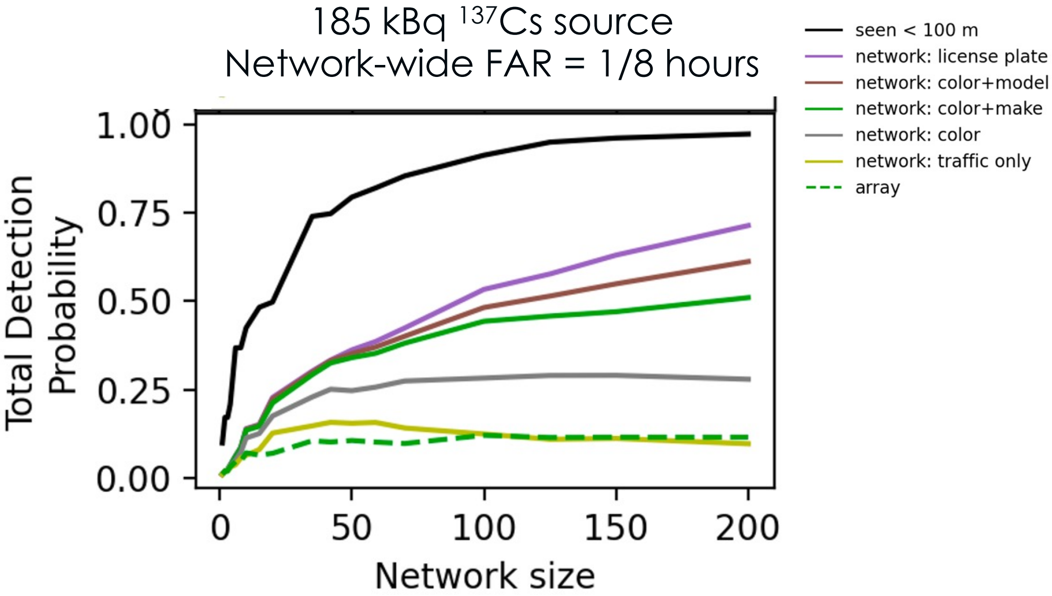


M.R. Marshall et. al., (2023) arXiv:2309.06592
M.R. Marshall et. al., (2020), DOI:10.1109/TNS.2020.3047646

Network Data Fusion (Simulation)

- Simulation of vehicle-borne ^{137}Cs sources through city-scale, multi-sensor networks
- 'Fusion' of data from correlated observations improves detection sensitivity





$$SNR = \frac{S_{total}}{\sqrt{S_{total} + B_{total}}}$$

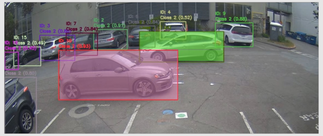
Source counts

Background counts

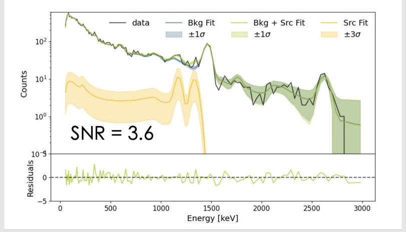
E. Rofors et. al., (2025), DOI: 10.1109/TNS.2024.3518392

Network Data Fusion (Experimental)

First sub-threshold observation



Initial sub-threshold observation (spectrum A)



2MBq ^{60}Co source

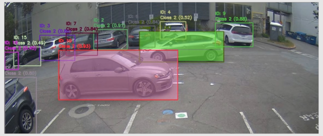
Source in vehicle #2 (green)

- Initial observation shows possible presence of a source, but below detection threshold
- Two vehicles in the field of view
  - Source is in vehicle #2 (green)
- Triggers vehicle re-identification neural network
  - Looks out for these specific vehicles!

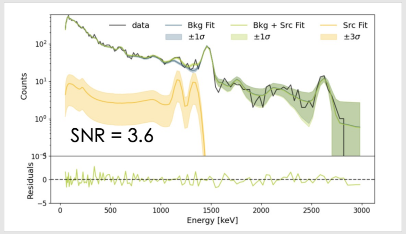
TransReID arXiv:2102.04378

Network Data Fusion (Experimental)

First sub-threshold observation

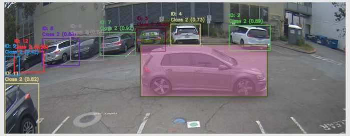


Initial sub-threshold observation (spectrum A)

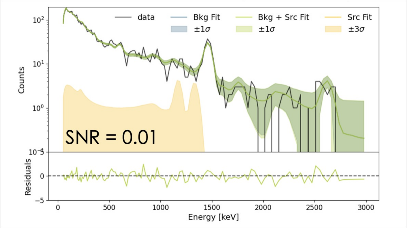


2MBq ^{60}Co source

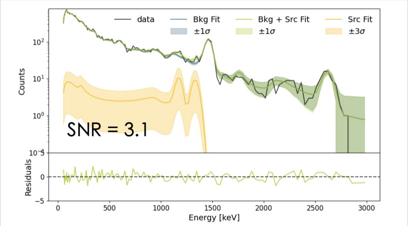
Subsequent observation of vehicle-of-interest #1



Observed spectrum (spectrum B)



Fused spectrum (A+B)



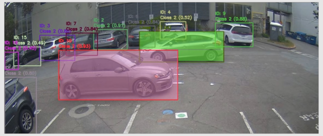
- Second observation of vehicle #1, SNR still below threshold

BERKELEY LAB

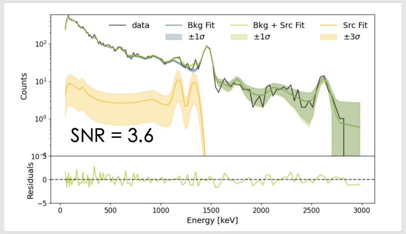
NUCLEAR SCIENCE DIVISION

Network Data Fusion (Experimental)

First sub-threshold observation

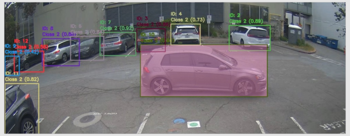


Initial sub-threshold observation (spectrum A)

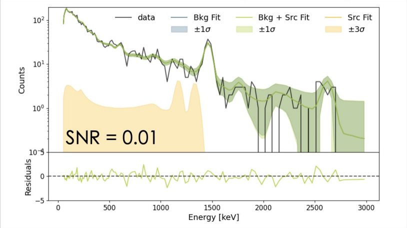


2MBq ^{60}Co source

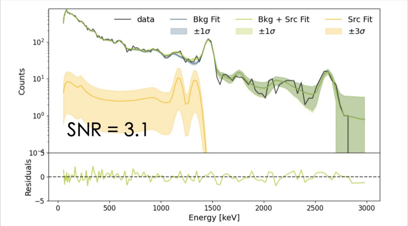
Subsequent observation of vehicle-of-interest #1



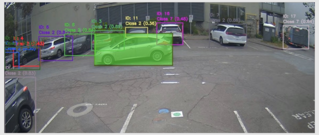
Observed spectrum (spectrum B)



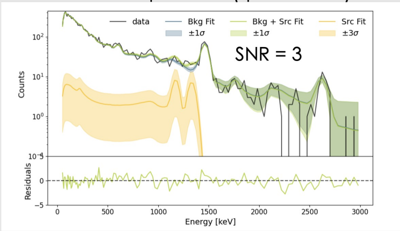
Fused spectrum (A+B)



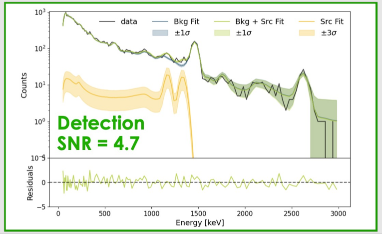
Subsequent observation of vehicle-of-interest #2



Observed spectrum (spectrum C)



Fused spectrum (A+C)



Summary

- Real-world radiation detection is not advanced by nuclear physics alone!
- Understanding radiation detection principles, sensing more broadly, and how to combine these with advanced computational methods can unluck transformational new capabilities
- The transition of multi-modal sensing technologies into the field is underway and seems to be gaining momentum

Tutorial Questions

- What are the advantages and disadvantages of different detectors in real-world environments?

- What are some challenges in the field compared to the lab?

(Yesterday’s) Tutorial Questions

- What are the factors that influence the energy resolution in semiconductor and scintillation detectors?

- Why is the energy resolution of HPGe so much better than NaI?

- What factors affect the maximum active volume of a HPGe detector?

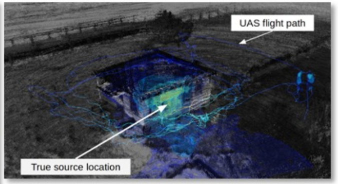
Evolution of Technologies

Over 15 years of development of sensor systems and algorithms

Static Lidar, cart-based imager

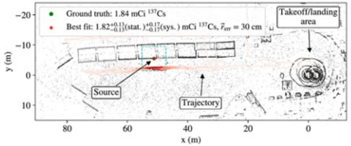
DOI: 10.1109/TNS.2009.2015304

Compact 3D imaging and mapping
Multiple platforms; Lidar and video



arXiv:1901.05038

Quantitative imaging

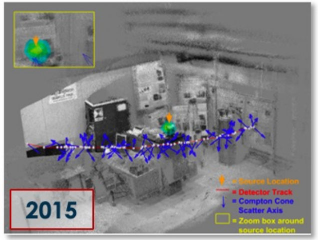


DOI: 10.1038/s41598-021-99588-z

Autonomy and multi system fusion

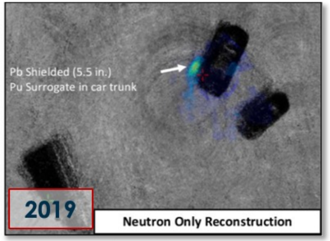
AI-driven autonomy

Real-time 3D imaging
Cart-based imager plus MS Kinect



DOI: 10.1016/j.nima.2015.08.016

3D Neutron mapping



arXiv: 1908.06114

Object tracking systems

DOI: 10.1109/TNS.2020.3047646

City-scale multi-sensor networks

DOI: 10.1088/1742-6596/2586/1/012125

Thank you

Questions?

Photo Credit: Mark Bandstra, ANP