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Machine Learning and Data Fusion for Enhanced Radiation Detection, Localization, and Mapping

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Technical Meeting on Artificial Intelligence for Nuclear Technology and Applications
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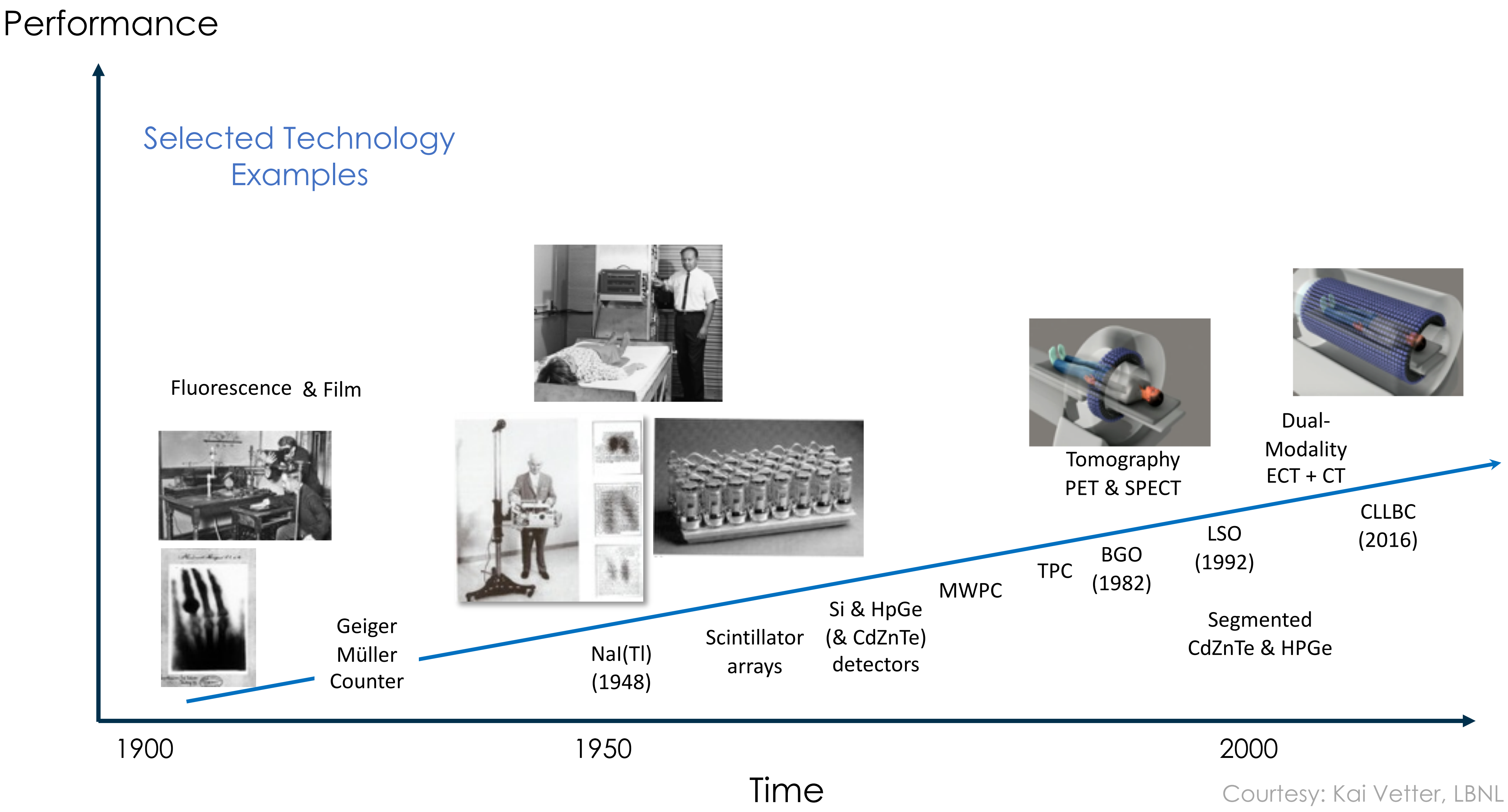
Examples of the use of ML/AI for:

- Radiological/nuclear source detection
- 3D radiation imaging and mapping
- Object detection and tracking
  - Enhanced detection and localization
  - Nuclear safeguards

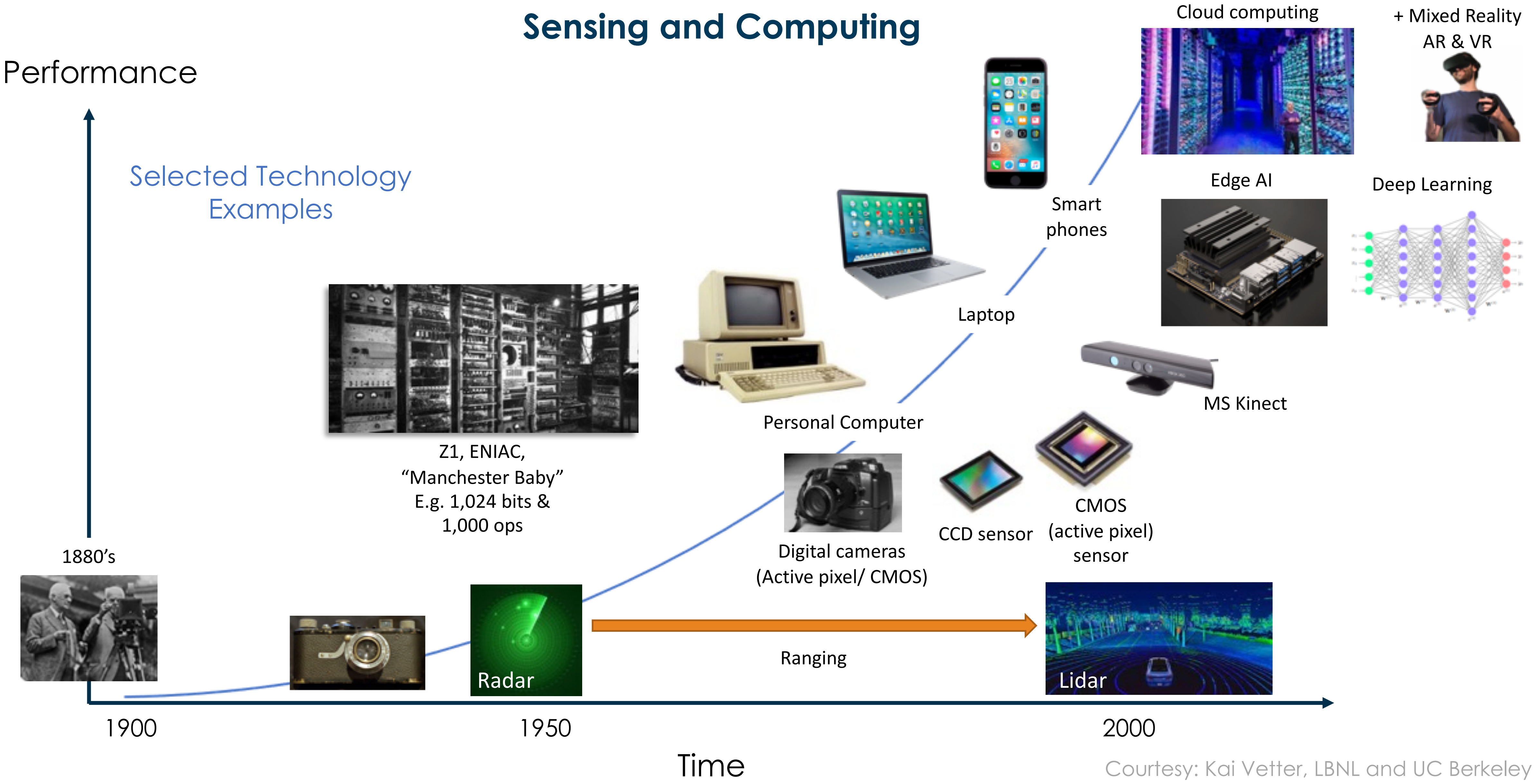
Evolution of Technology

Radiation Detection and Imaging



Courtesy: Kai Vetter, LBNL and UC Berkeley

Evolution of Technology

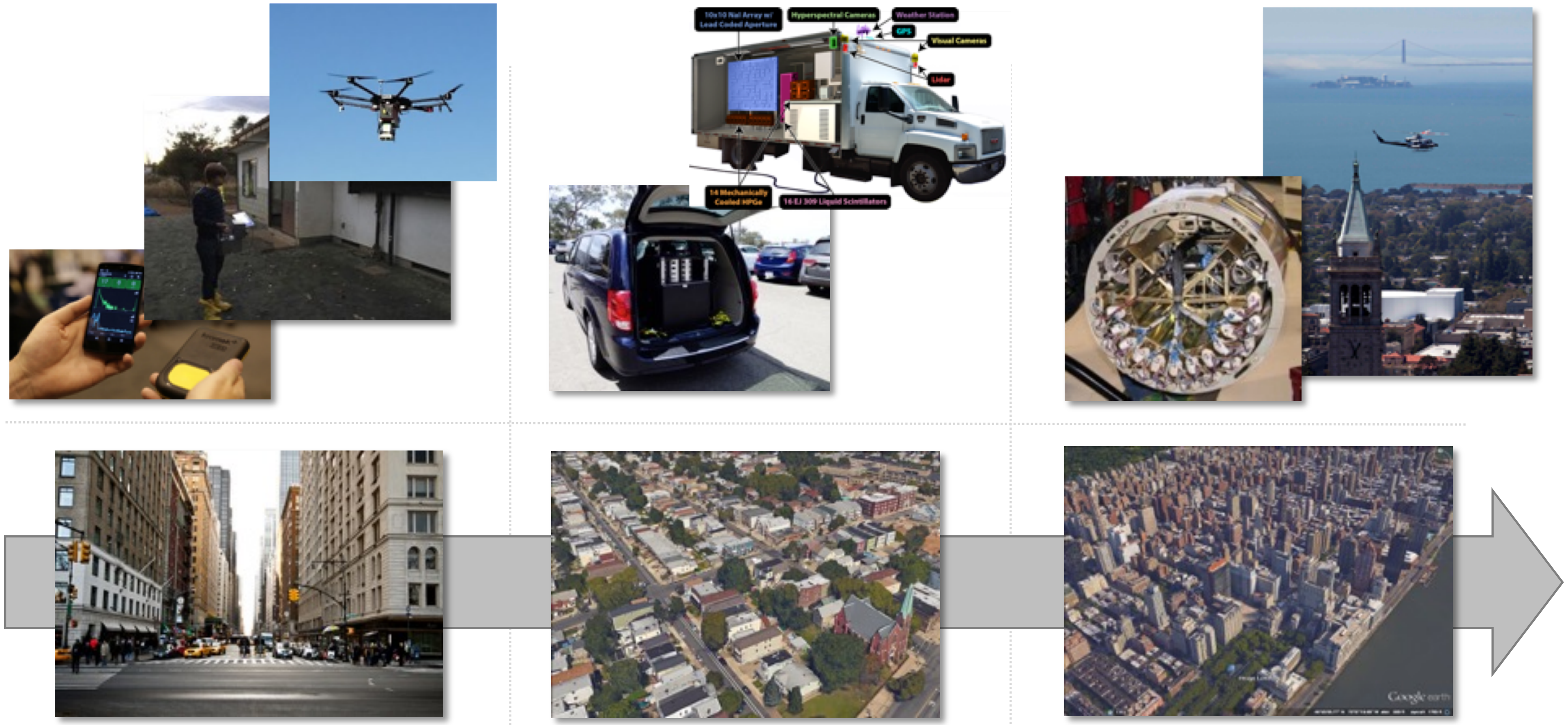


Courtesy: Kai Vetter, LBNL and UC Berkeley

Radiological/Nuclear Source Detection

R/N Source Search

Radiological search seeks to detect and identify anomalous radiological sources with high sensitivity in environments ranging from street to city scale



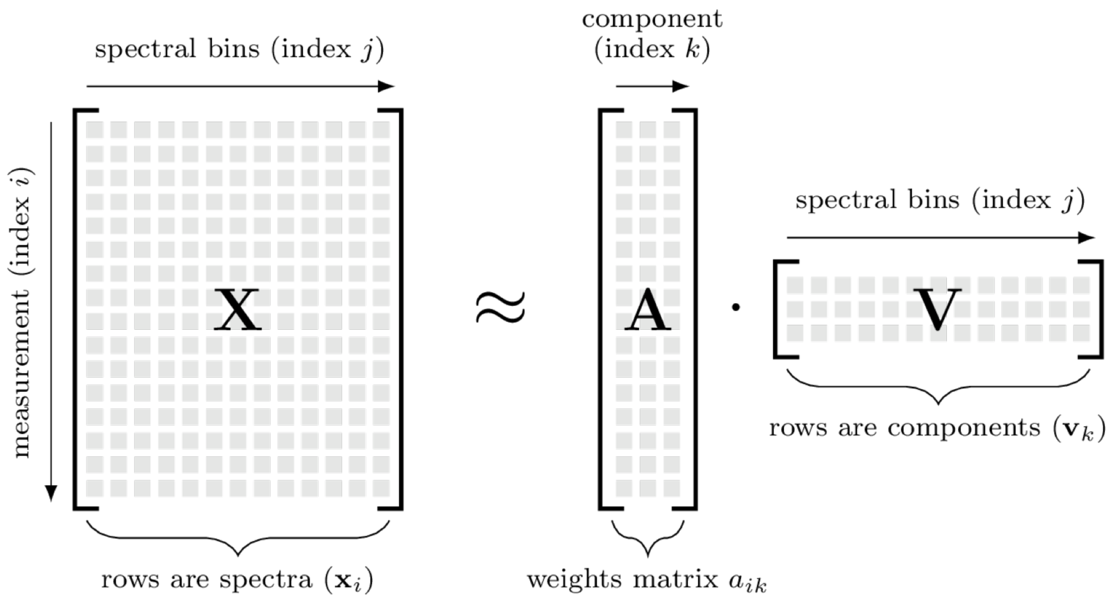
Street Scale **Block Scale** **City Scale**

Key Challenges:

- Short dwell times
- Weak and/or shielded sources
- Highly varying, unpredictable backgrounds
- Very low false positive rates (e.g. 1 in 10^5)

Non-Negative Matrix Factorization

- Decompose gamma-ray spectra into non-negative parts (components), consistent with Poisson statistics
  - Components can be used to form a background model



- Components are additive, non-orthogonal, and lend themselves well to physical interpretation

NMF: D.D. Lee & H.S. Seung, Nature (1999), DOI: 10.1038/44565

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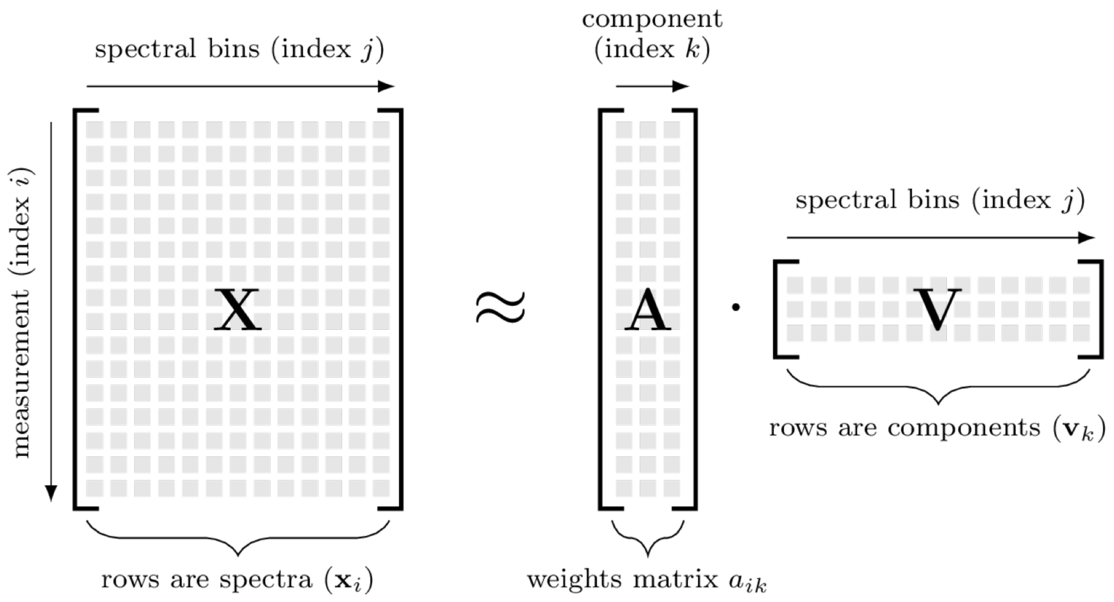
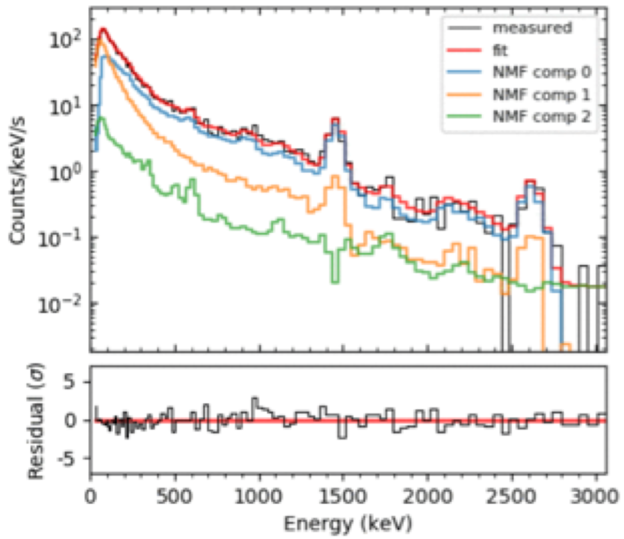
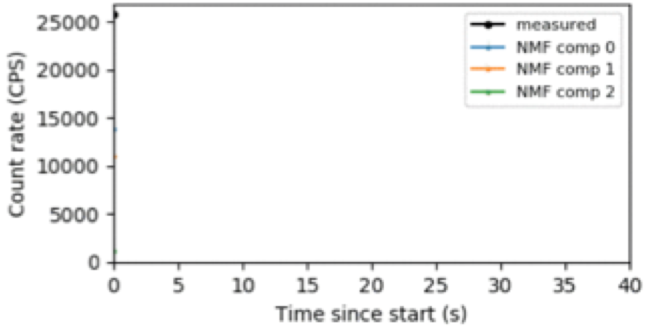
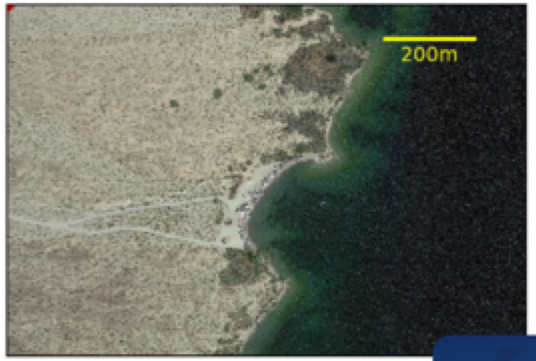


NaI detector data from Aerial Measurement System (AMS) at Lake Mohave, NV







- Components are additive, non-orthogonal, and lend themselves well to physical interpretation

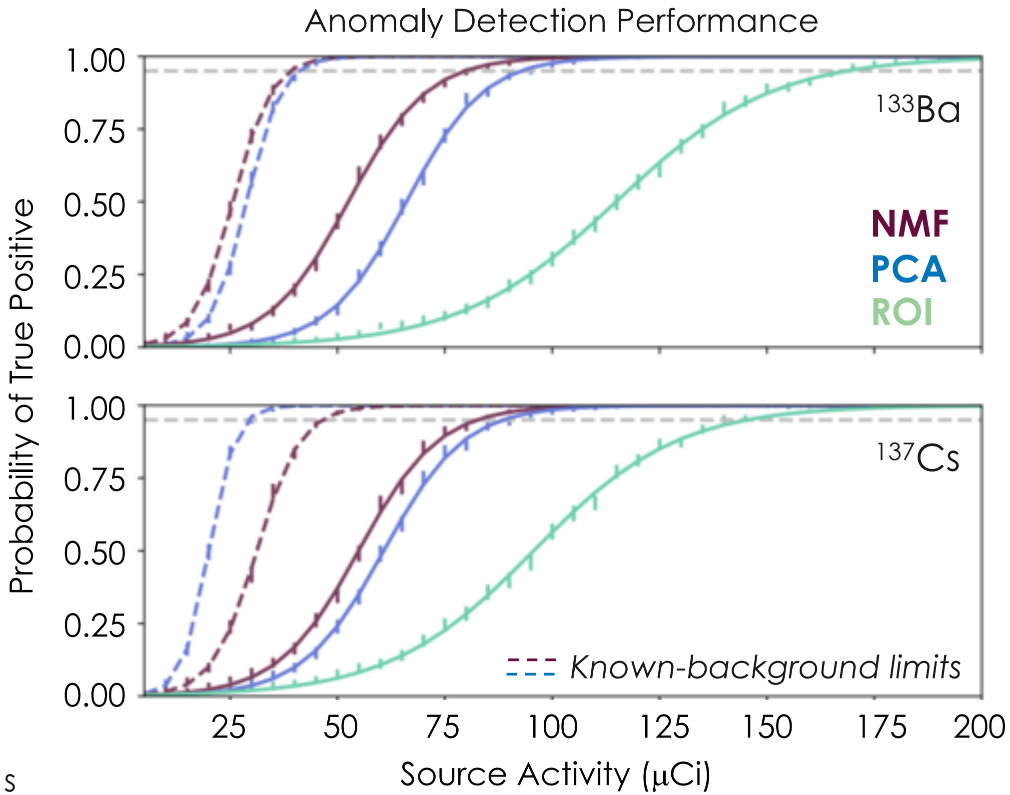
- "Distant terrestrial" decreases first
- "Nearby terrestrial" decreases later
- "Radon/cosmics/aircraft" remains approximately constant

NMF: D.D. Lee & H.S. Seung, Nature (1999), DOI: 10.1038/44565

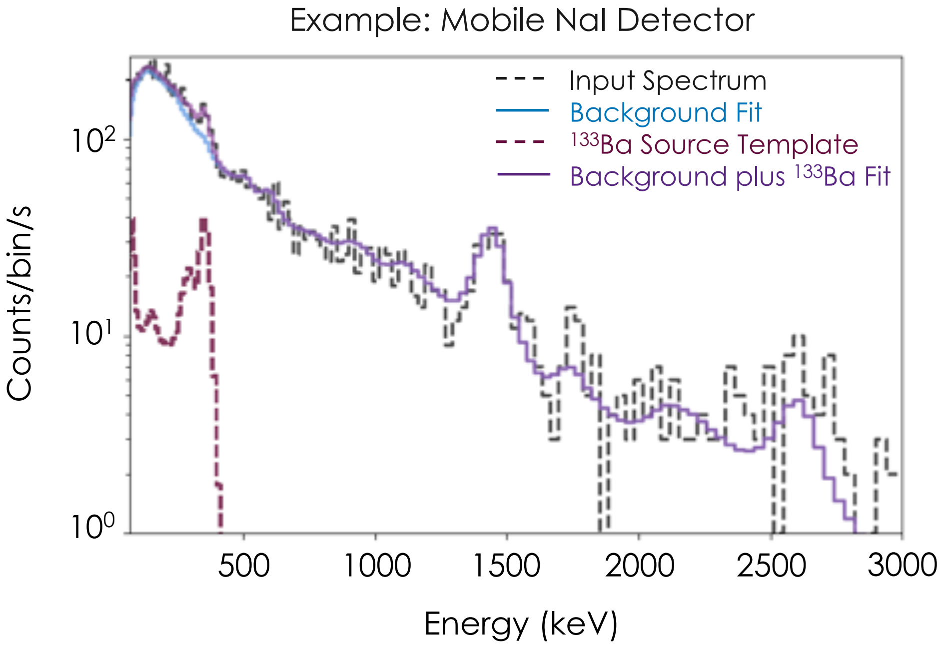
M.S. Bandstra *et al.*, IEEE TNS (2020) 10.1109/TNS.2020.2978798

NMF For R/N Source Detection and Identification

- **Anomaly Detection**: Test incident spectrum for consistency with background model (e.g. via Poisson deviance)
- **Isotope Identification**: Perform Likelihood Ratio Test between background only and background-plus-source hypotheses



Mobile NaI
Standoff = 20 m
Integration time = 1 s
FAR = 1/8 hours



- NMF-based methods significantly outperform other "mature" algorithms
- Still a factor of 2 away from *statistical limit*

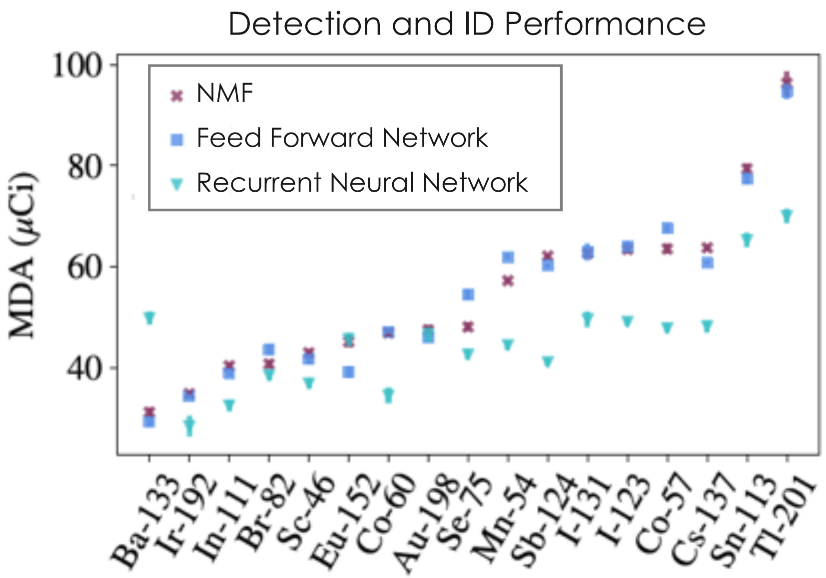
K.J. Bilton *et al.*, IEEE TNS (2019), DOI: 10.1109/TNS.2019.2907267

Neural Network Approaches

- Neural Network approaches have the potential to further improve rad/nuc detection and isotope ID

Example 1: RNN Based Detection and ID

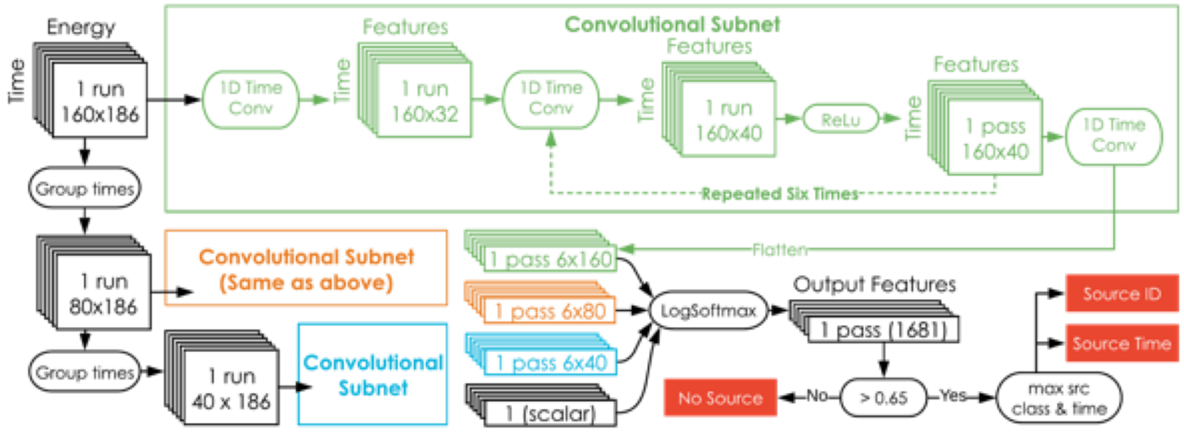
- Recurrent Neural Network outperformed NMF



K.J. Bilton *et al.*, J. Nucl. Eng. (2021), DOI: 10.3390/jne2020018

Example 2: Urban Radiological Search Competition (DOE NNSA, 2019)

- Neural networks significantly outperformed winners of a prior national laboratory competition



Competition Data - DOI: 10.13139/ORNLNCCS/1597414

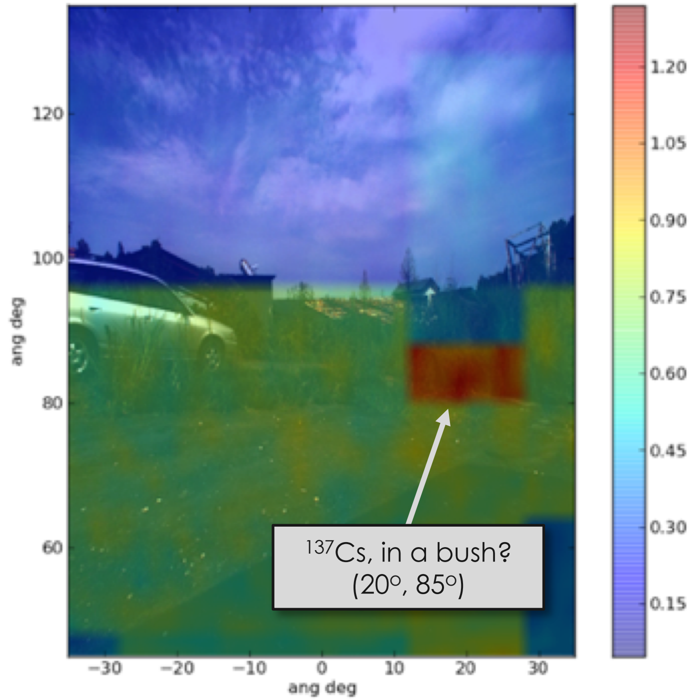
See presentation by Tenzing Joshi

3D Radiation Imaging and Mapping

Free-Moving 3D Imaging and Mapping

Conventional radiation imaging:

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



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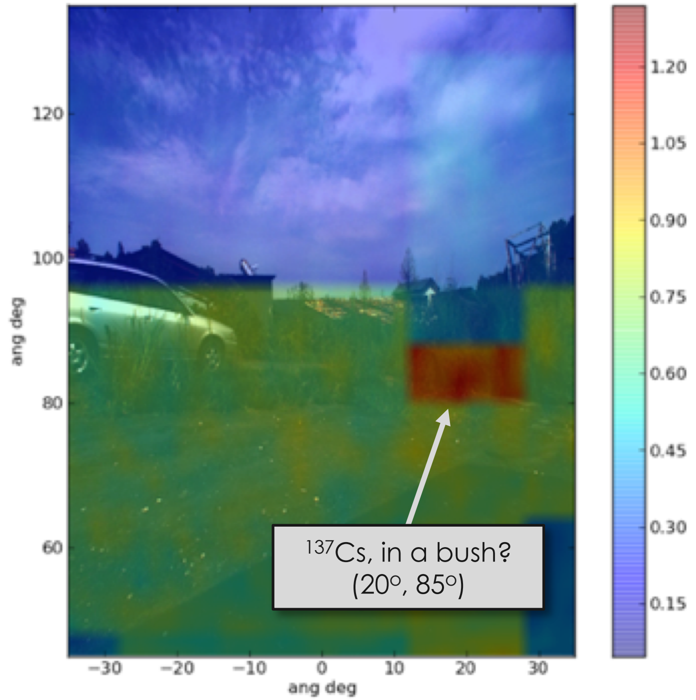
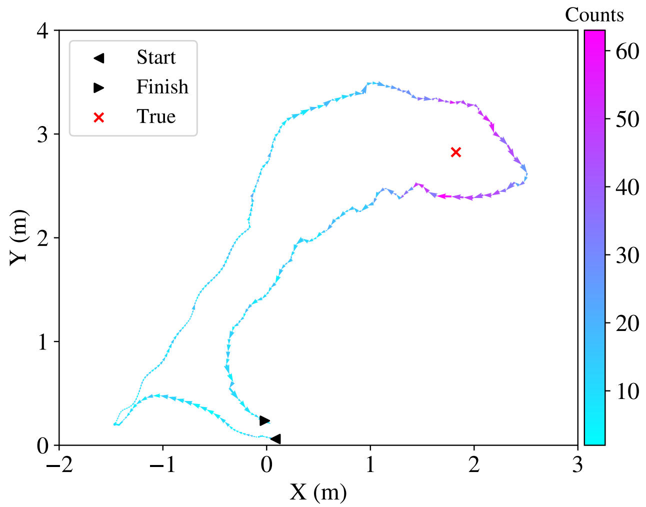
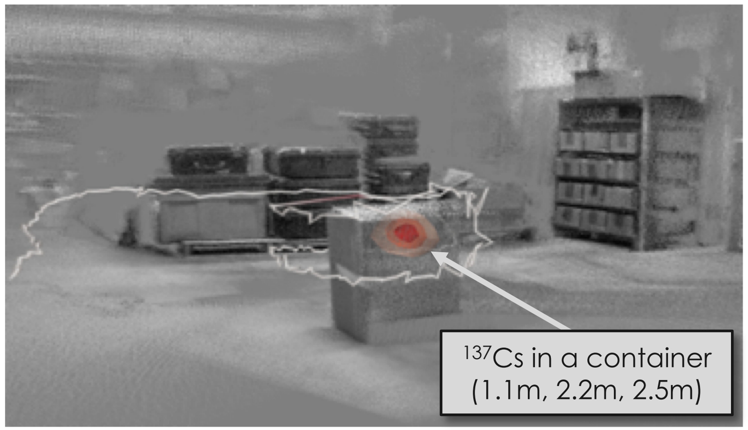


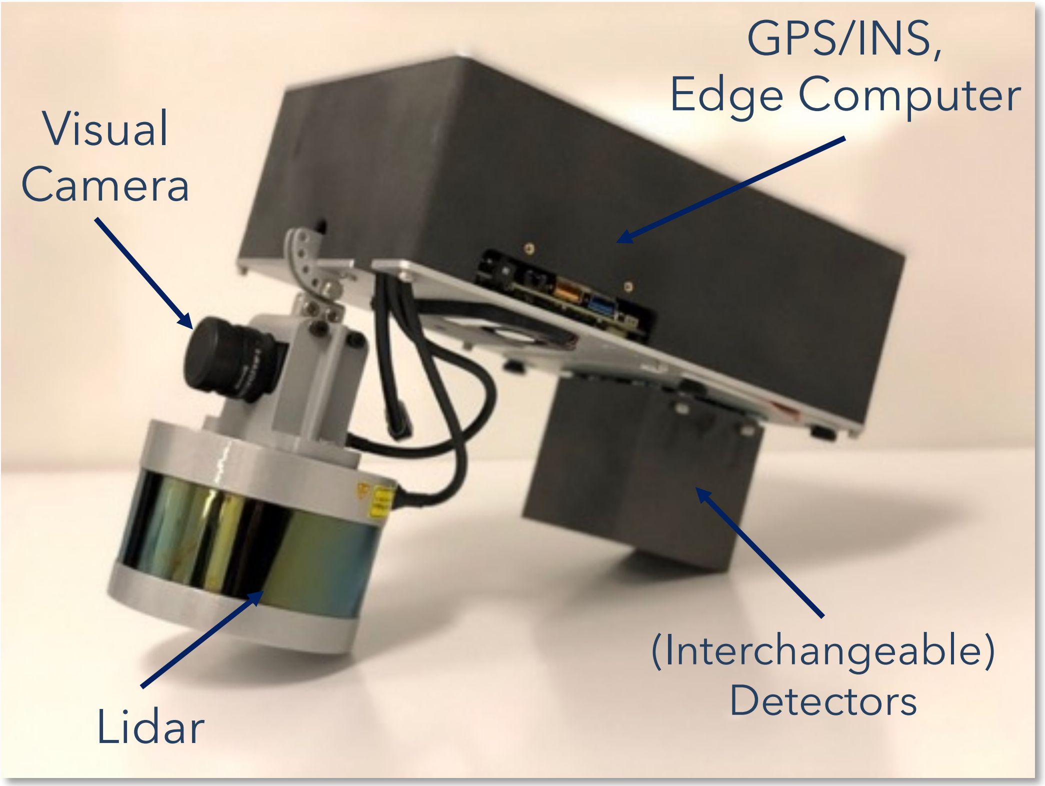


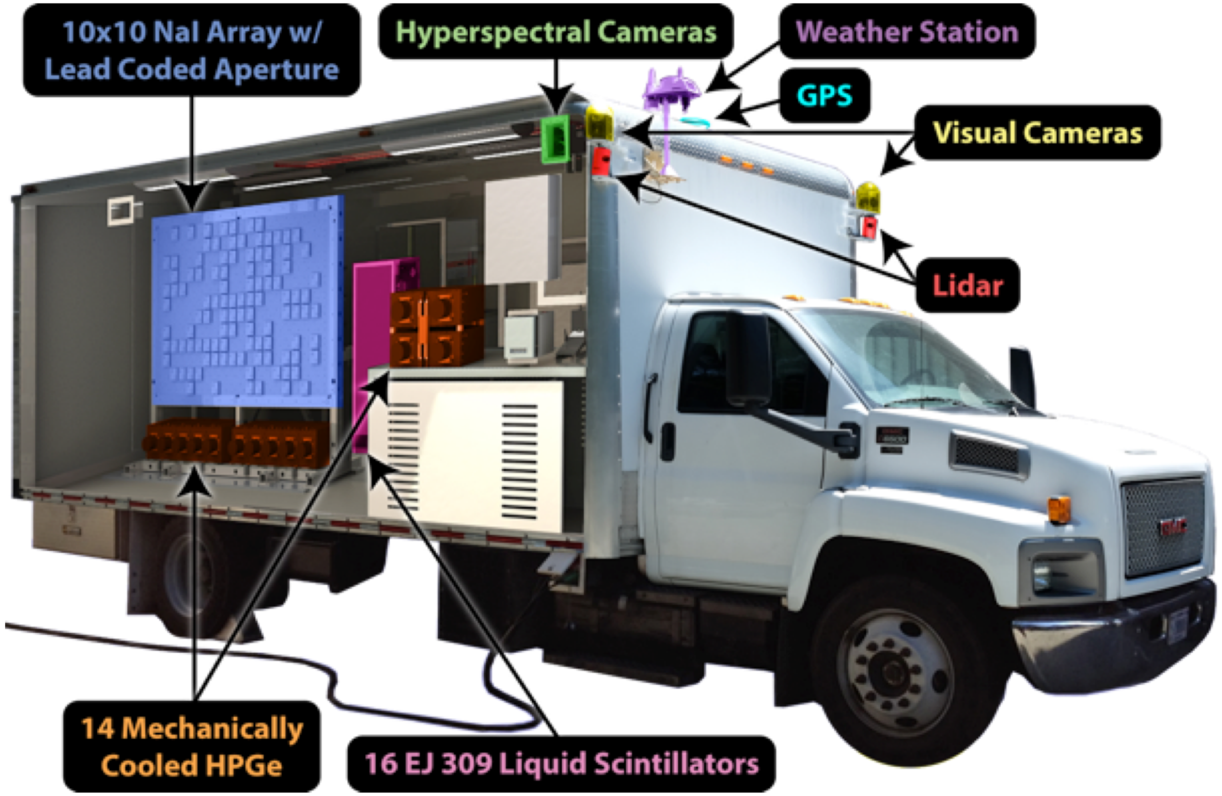


Free-moving radiation imaging:
- Overcomes $1/r^2$ limitations and increases sensitivity
- Enables 3D imaging
- Uses modulation by motion and detector response
- Does not require an imaging system

Requirements:
- Knowledge of detector response
- Continuous tracking of system pose

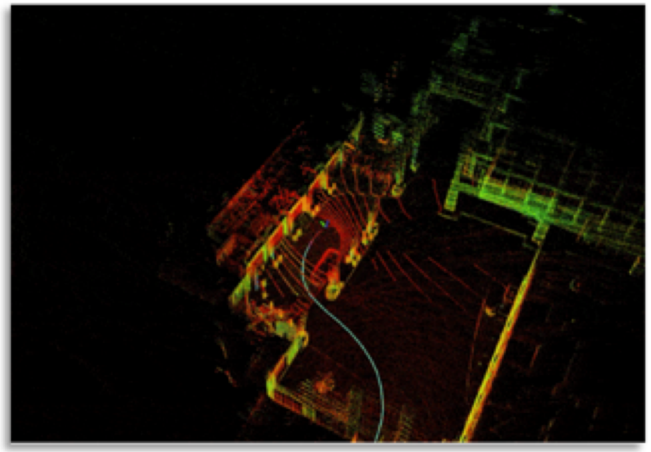
Contextually Enhanced Radiation Detectors





3D Scene Data Fusion

- Simultaneous Localization and Mapping and Localization (SLAM)[1] algorithms provide:
    I. 3D model of the environment
    II. Estimate of system position and orientation



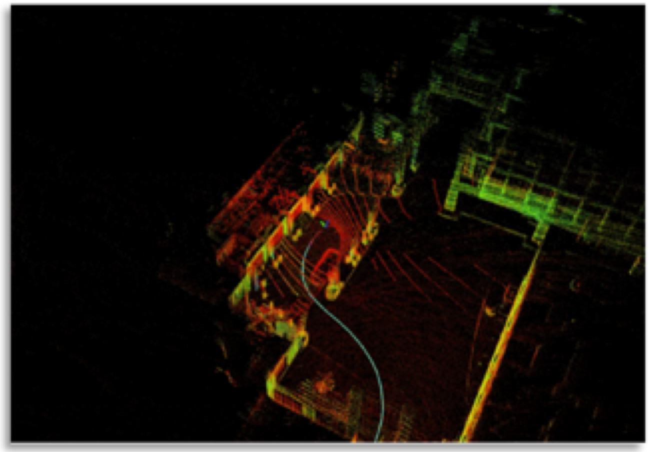
LIO-SAM: https://github.com/TixiaoShan/LIO-SAM

[1] H. Durrant-Whyte & T. Bailey (2006), DOI: 10.1109/MRA.2006.1638022

3D Scene Data Fusion

- Simultaneous Localization and Mapping and Localization (SLAM)[1] algorithms provide:
  - I. 3D model of the environment
  - II. Estimate of system position and orientation

- Continuous fusion of radiation data with SLAM output allows 3D mapping and visualization of radiation field in real time [2,3,4]



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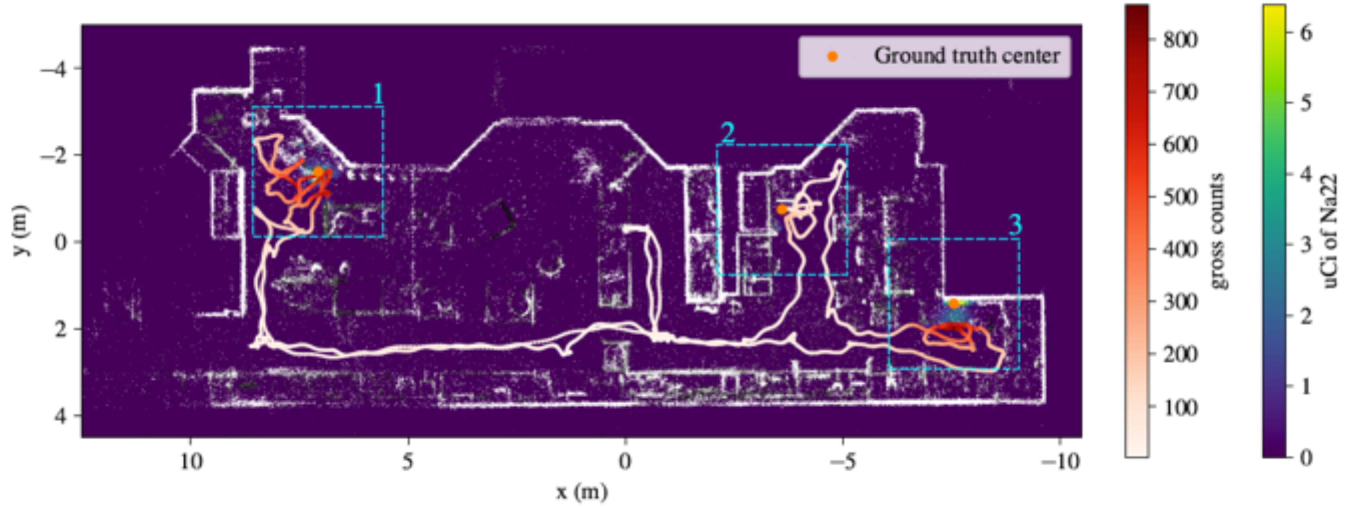


- Future directions include exploring Deep SLAM/Spatial AI[5]

[1] H. Durrant-Whyte & T. Bailey (2006), DOI: 10.1109/MRA.2006.1638022

[5] A. Davison (2018), arXiv:1803.11288v1

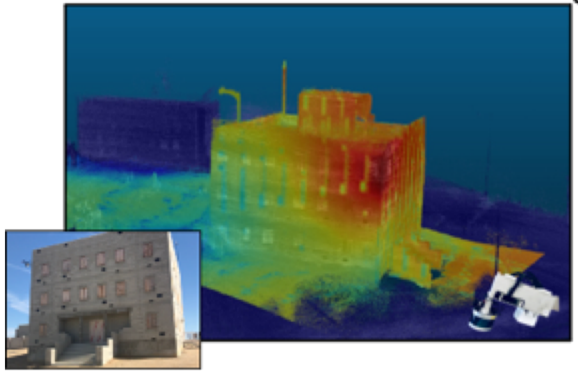
[2] R. Barnowski *et al.*, NIM A (2015), DOI: 10.1016/j.nima.2015.08.016

[3] K. Vetter *et al.*, Sensors (2019), DOI: 10.3390/s19112541

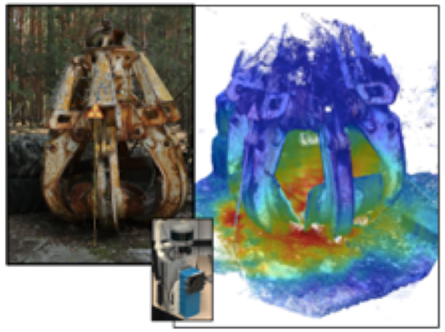
[4] D. Hellfeld *et al.*, Sci. Rep. (2021) DOI: 10.1038/s41598-021-99588-z

3D Scene Data Fusion Examples

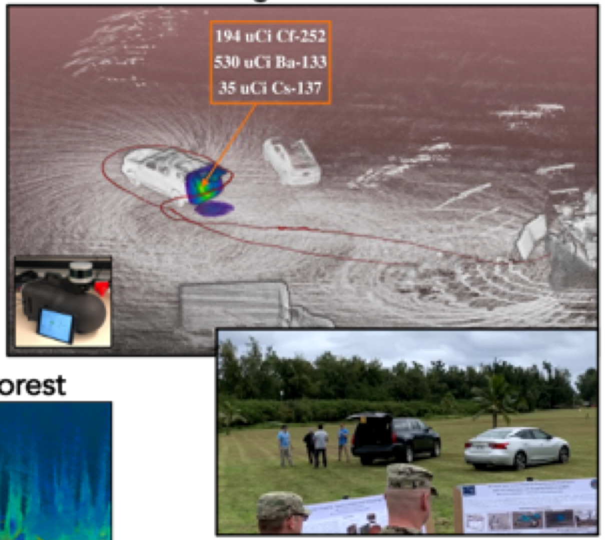
Source localization in concrete building



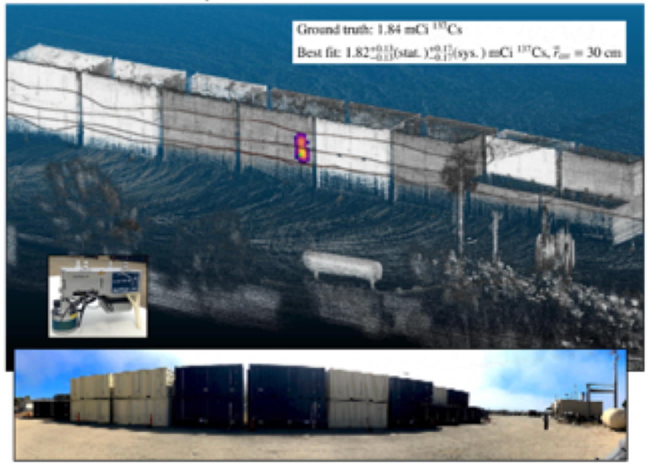
Chernobyl claw



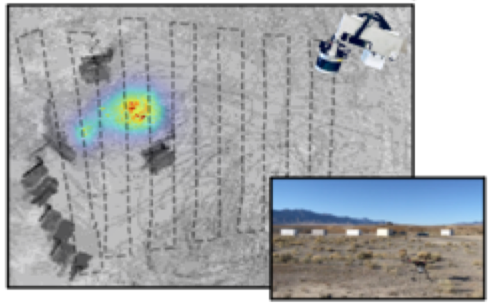
Pu-surrogate localization



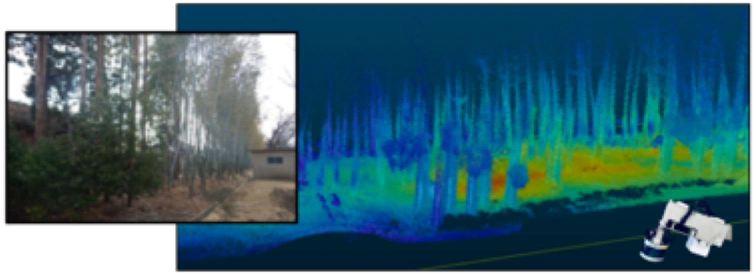
Point-source quantification in container stack



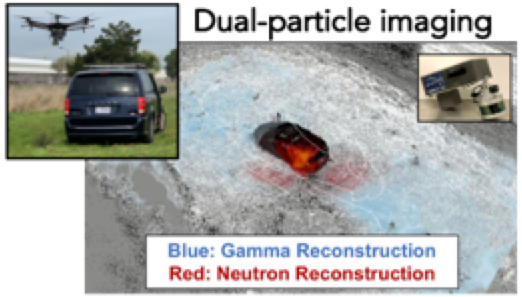
Br-82 detonation aerial survey



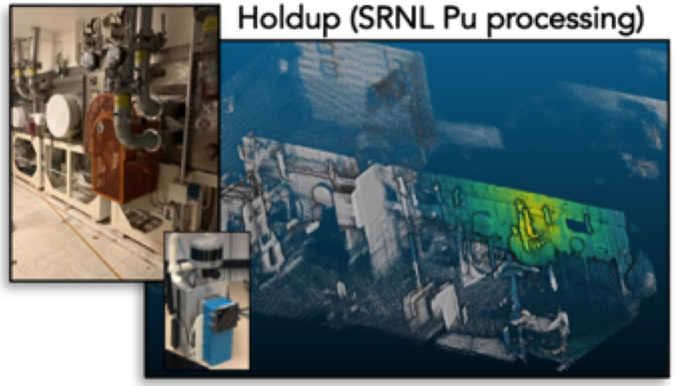
Contaminated Fukushima bamboo forest



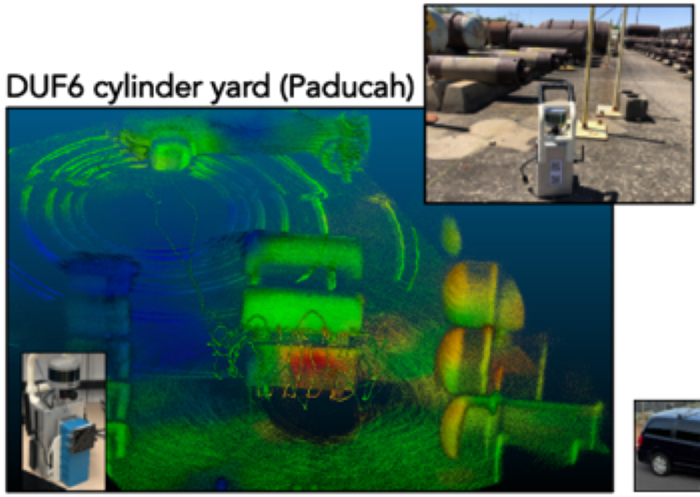
Dual-particle imaging



Holdup (SRNL Pu processing)



DUF6 cylinder yard (Paducah)

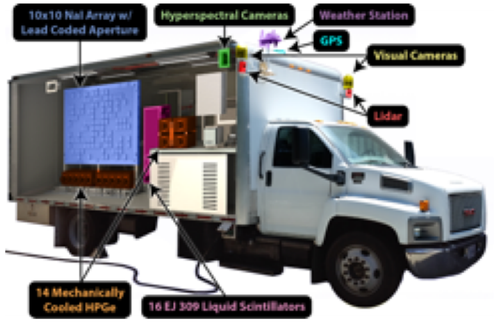


Wide-area mapping (70 lot LBL)

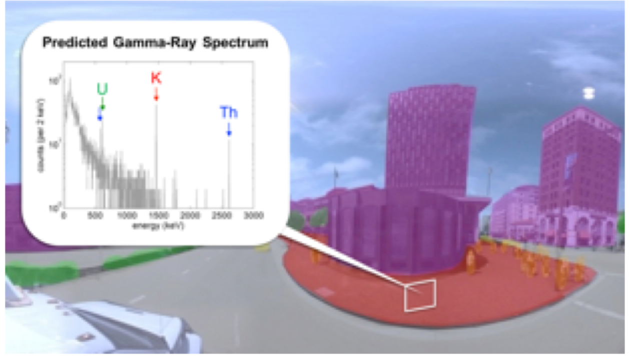
"Nuclear Street View"

- AI for object detection and semantic segmentation of visual imagery
- Towards prediction of radiological backgrounds from video and Lidar

RadMAP



"Nuclear Street View" Concept



RadMAP: M.S. Bandstra *et al.*, NIM A(2016), DOI: 10.1016/j.nima.2016.09.040

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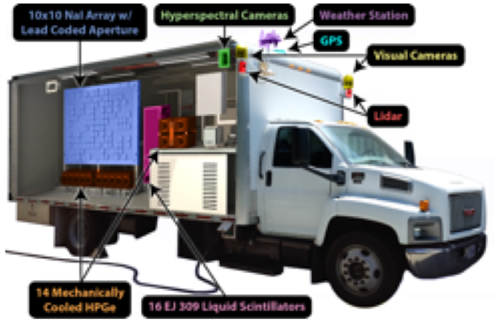
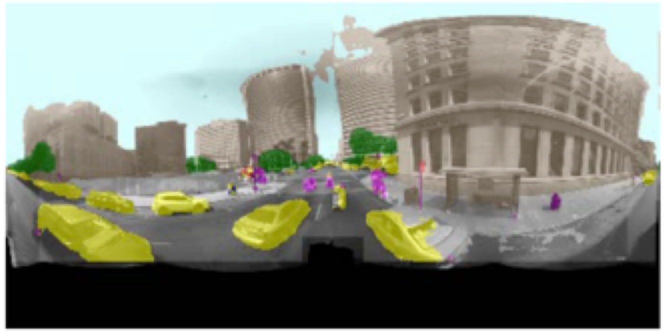


Semantic Segmentation of Video



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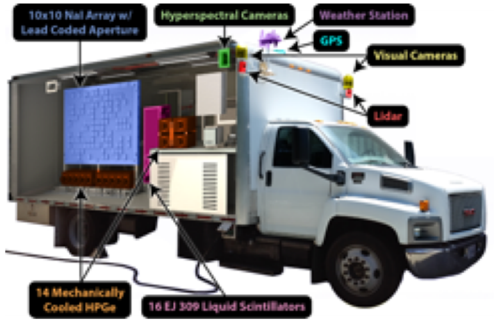

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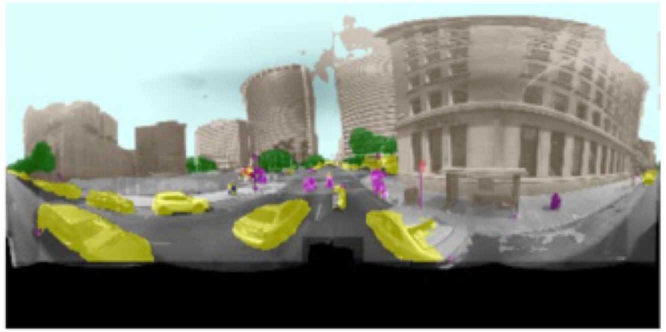
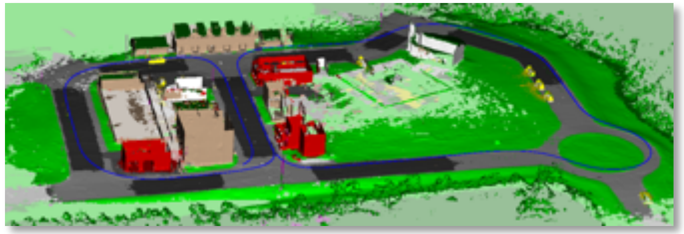
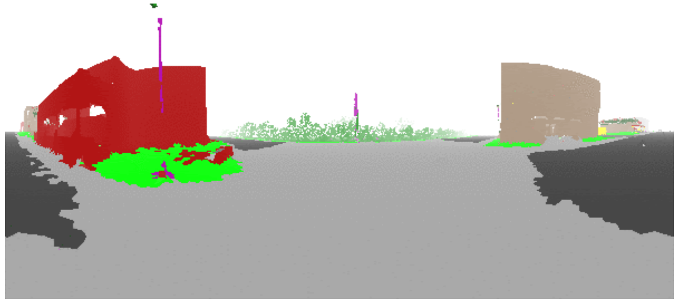


Fort Indiantown Gap (FIG)
National Guard Base

3D Mesh with Labels Applied





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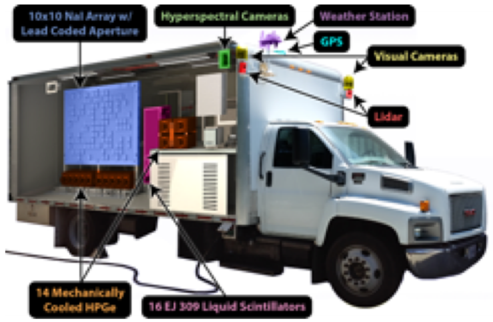

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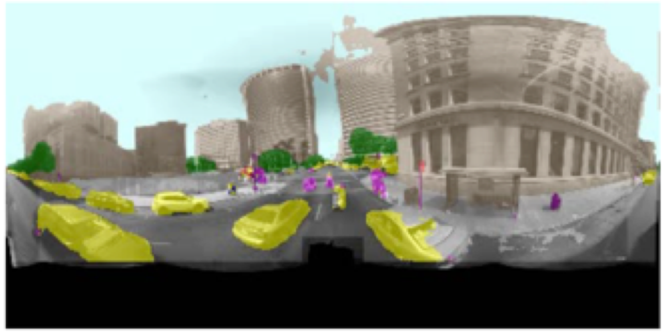

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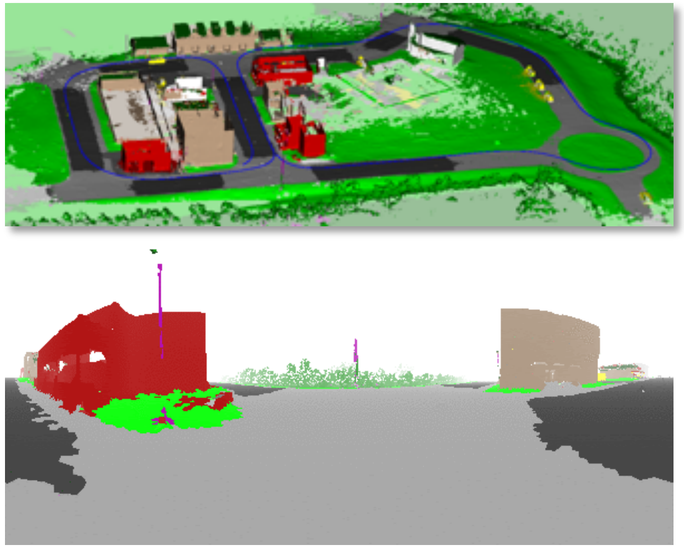
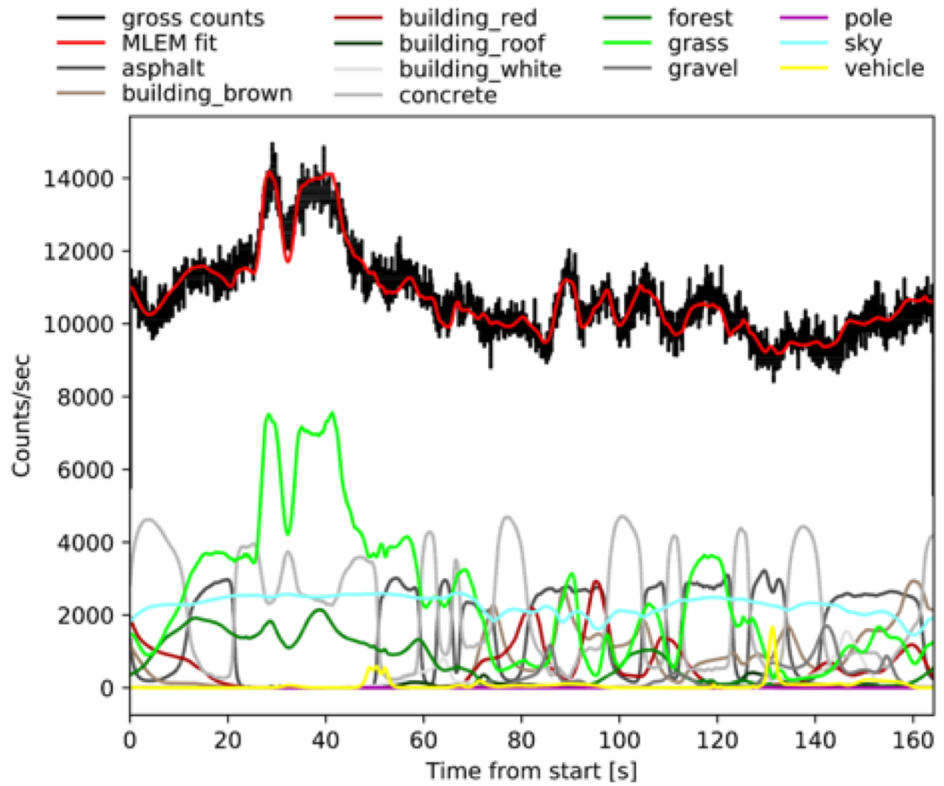


Fit to spectral data based on 3D projections of semantic segments

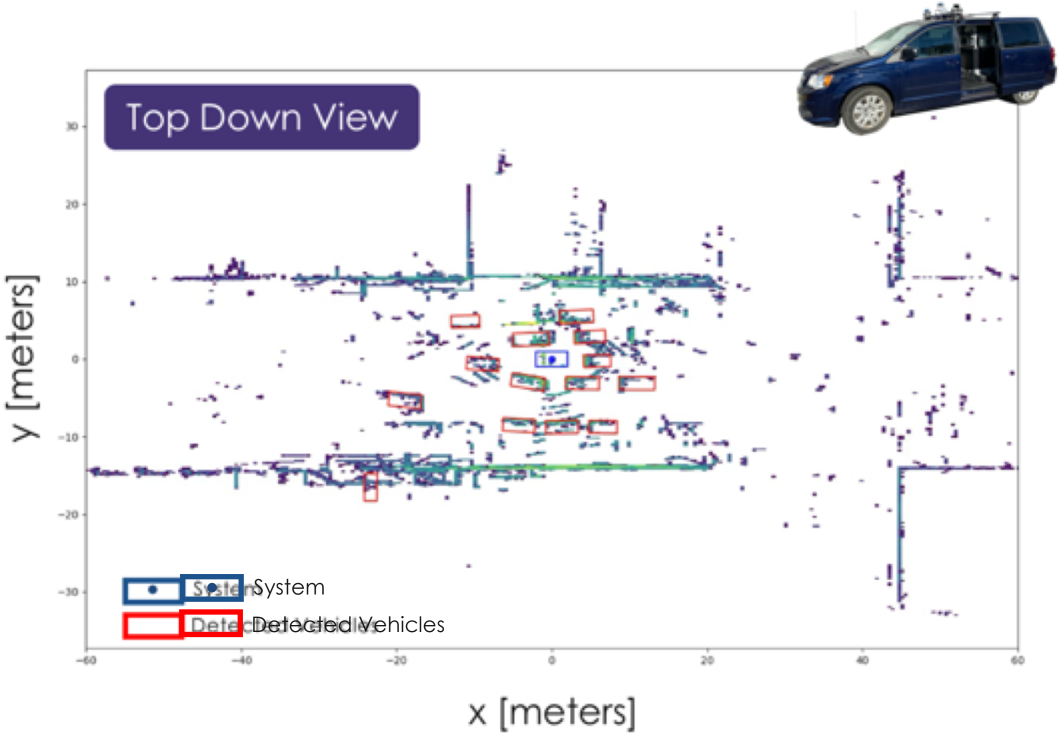


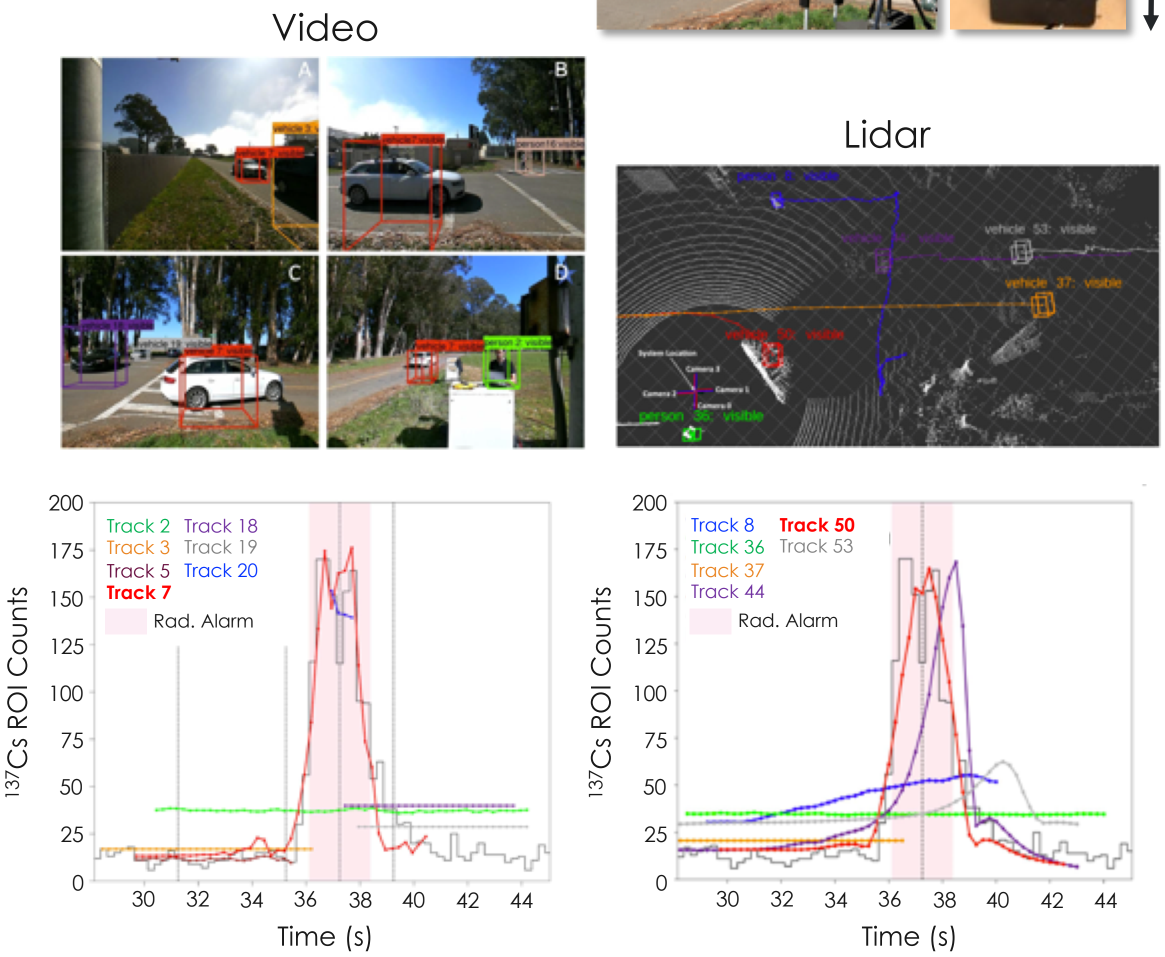
M. Salathe *et al.*, Phy. Rev. Research (2021), DOI: 10.1103/PhysRevResearch.3.023070

Object Detection and Tracking

Object Detection and Tracking for Enhanced Detection

- Real-time object detection with video and Lidar using CNNs
  - e.g. YOLO v3/v4 (video), PointPillars (Lidar)
- 3D object tracking e.g. with Kalman filter
- **Attribution of radiological signals to tracked objects provides:**
  - **Localization**
  - **Situational awareness**
  - **Improved detection sensitivity**

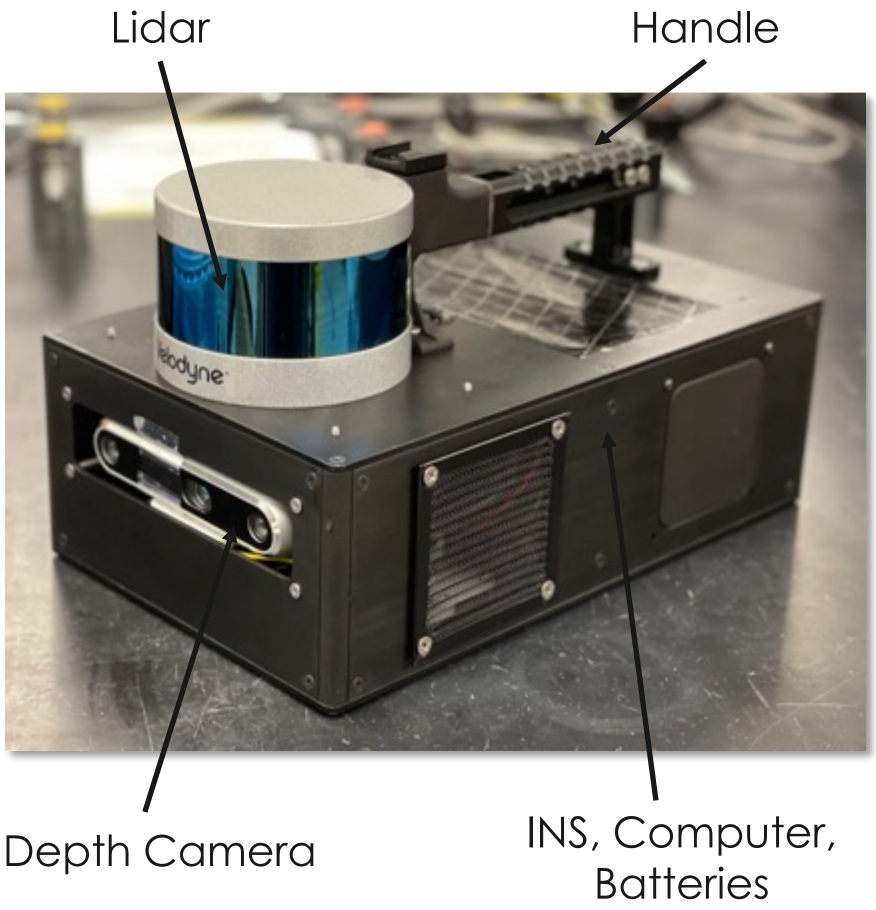


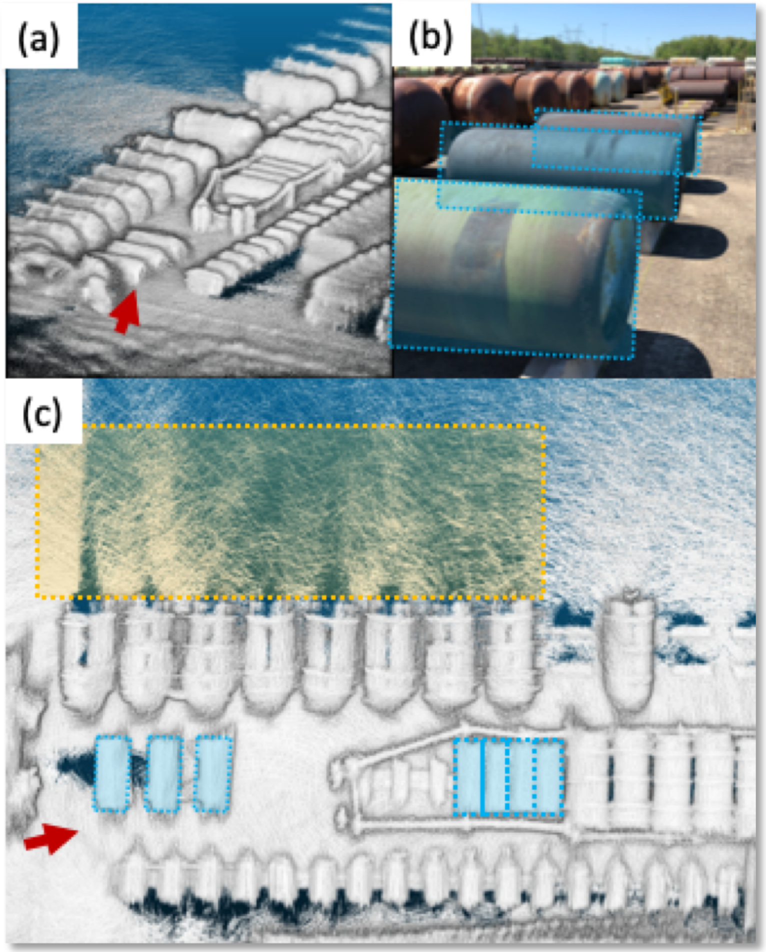


M.R. Marshall *et al.*, IEEE TNS(2020), DOI: 10.1109/TNS.2020.3047646

Object Detection for Nuclear Material Accountancy

- Compact, multi-sensor systems and AI algorithms can replace manual object counting and accountancy in nuclear safeguards and treaty verification applications

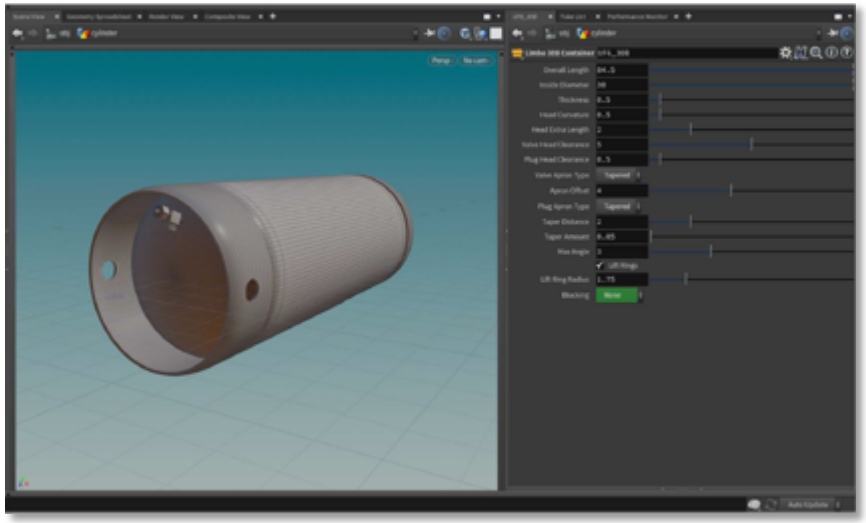




Object Detection for Nuclear Material Accountancy

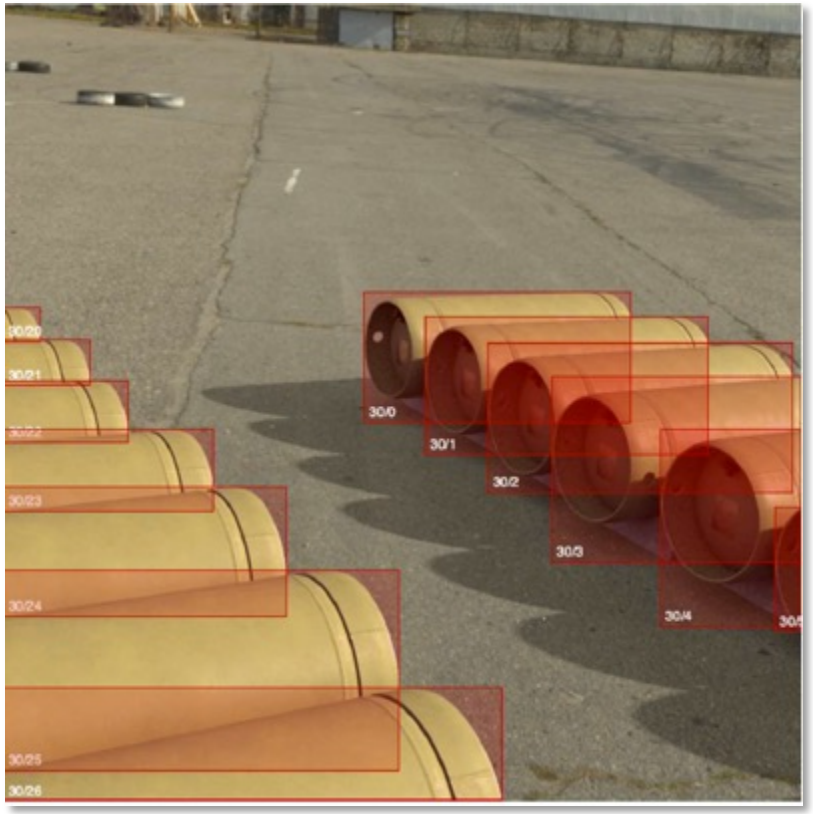
- Efforts are underway to develop large, synthetic data sets for training and testing image-based detection, identification, and classification algorithms

3D CAD Model of UF6 Container



Placed in Real 3D Environments and Rendered into 2D Images

Automatically Labelled



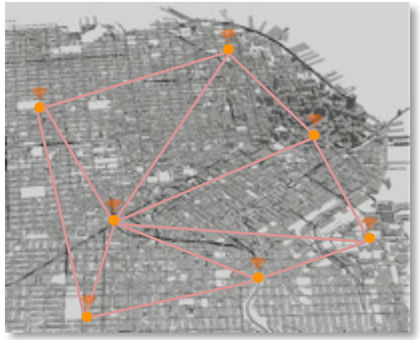
Sandia National Laboratories

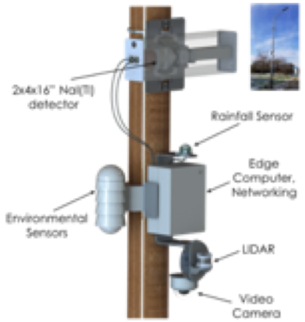
Images: Zoe Gastelum, Sandia National Laboratories

Some Things I Didn't Cover…

Distributed Sensor Networks and 5G

- Networked, multi-sensor systems for urban environments
- AI at the edge
- Network data fusion
- 5G: AI-drive optimization of data network

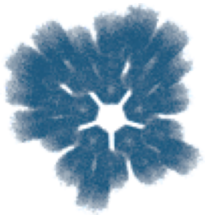




Online Learning of Radiological Backgrounds and Anomalies

- Ab-initio learning of NMF background models
- Physics-based online updating of background models and anomalous source signatures

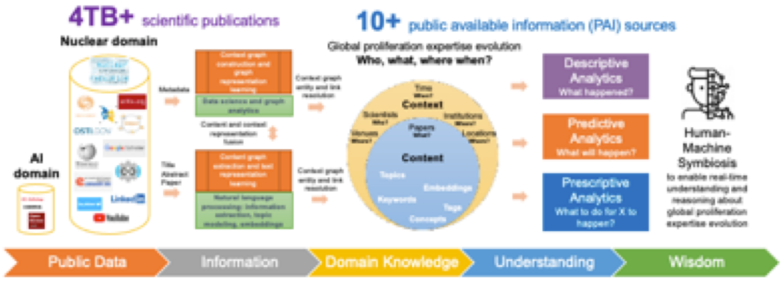
ML/AI in Low Energy Nuclear Physics



- Real-time optimization of experimental systems
- Optimization of ion sources
- Reinforcement learning for signal decomposition
- Physics-based AI for gamma-ray tracking

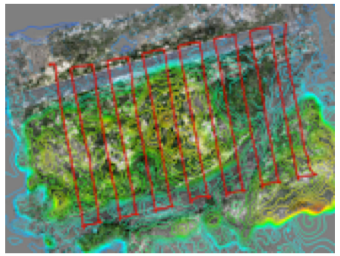
Natural Language Processing and Open Source Analytics (Svitlana Volkova, PNNL)

- Analysis of open source data to explain and predict radiological observations
- Analysis of publicly available information to detect, monitor and forecast nuclear proliferation



UAS Swarms: Data Fusion and Navigation Policy

- Real-time fusion of radiological and contextual data from multiple systems
- Q-learning based navigation policy
- AR/VR for visualization and control



Summary

- Contextual sensing, Machine Learning, and Artificial Intelligence are enabling entirely new capabilities for radiation detection and imaging
- These new capabilities have a wealth of applications in nuclear security, safety, decommissioning, and environmental management
- Machine Learning and Artificial Intelligence methods have never been more accessible
- They will continue to play a major role in advanced radiation detection well into the future
  - e.g. sensor networks, autonomous systems

Thank You!

Acknowledgements: Nico Abgrall, Mark Bandstra, Kyle Bilton, Josh Cates, Joey Curtis, Micah Folsom, Dan Hellfeld, Tenzing Joshi, Matt Marshall, Alex Moran, Victor Negut, Ryan Pavlovsky, Brian Quiter, Emil Rofors, Marco Salathe, Kai Vetter, Kris Zieb

(Berkeley Applied Nuclear Physics Program)

Work supported by: DTRA, DHS CWMD, DOE NNSA,

RJCooper@lbl.gov

Photo Credit: Mark Bandstra, ANP