Drones for Radiation Sensing and Environmental Remediation

Dr. Jonathan Rogers
Lockheed Martin Professor of Avionics Integration
Georgia Institute of Technology

AREAL
Aerial Robotics and Experimental Autonomy Lab

Research in Drones, Sensing, and Robotics:

- Expertise in robotics, autonomy, sensing, and estimation
- Variety of drone flight test platforms
- Indoor and outdoor flight test locations
- Projects involving autonomous aircraft design, flight control, human interface
- Research sponsored by DOE/NNSA, NASA, DOD, DARPA, NSF

Georgia Tech
CREATING THE NEXT

Radiological Search and Source Term Estimation

S. Kemp, S. Kumar, C. Bakker, J. Rogers, "Real-Time Radiological Source Term Estimation for Multiple Sources in Cluttered Environments," *IEEE Transactions on Nuclear Science, Vol. 70, No. 11, 2023, pp. 2406-2419.*

S. Kemp, M. Duce, S. Kumar, A. Erickson, J. Rogers, "Radiological Source Term Estimation and Isotopic Identification with Parallel Log Domain Particle Filters," *IEEE Transactions on Nuclear Science*, Vol. 71, No. 11, 2024, pp. 2422-2431.

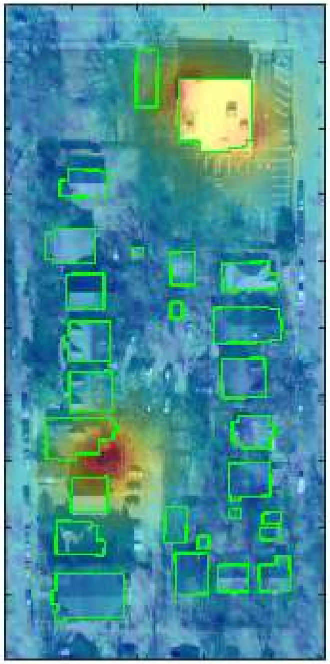
Funded by DOE NNSA, collaboration with PNNL

Algorithms for Autonomous Radiological Source Search

- Source Term Estimation (STE) with autonomous air and/or ground vehicles in **cluttered environment**
  - Arbitrary number of radioactive point sources of varying activities and isotopes.

- Source Term Estimation
  - How many sources are there?
  - Where are they?
  - What is their activity?
  - What isotope?

- **Cluttered Environment:** Obstacles are present. Obstacle/terrain information is known or can be approximated.

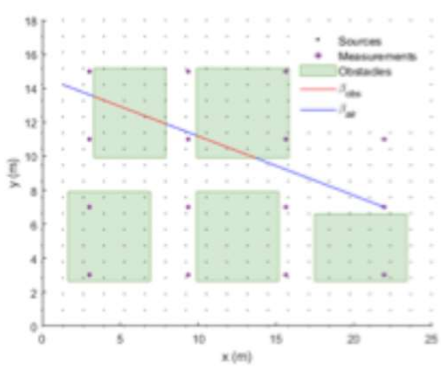


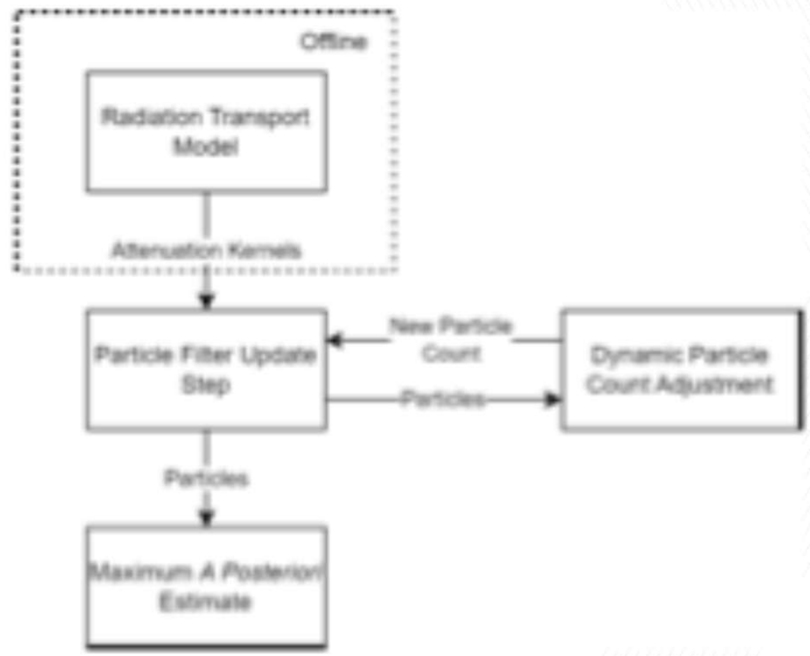
Example environment: obstacles outlined in green, radiation field due to 3 sources shown as heatmap.

Georgia Tech
CREATING THE NEXT

Algorithms for Autonomous Radiological Source Search

- “Particle filter” – Bayesian filter algorithm that generates random hypotheses about where sources are
- Measurements are used to continually refine “particle” set
- Radiation transport computations performed offline and then stored





Kemp *et al*, IEEE TNS, 2023.

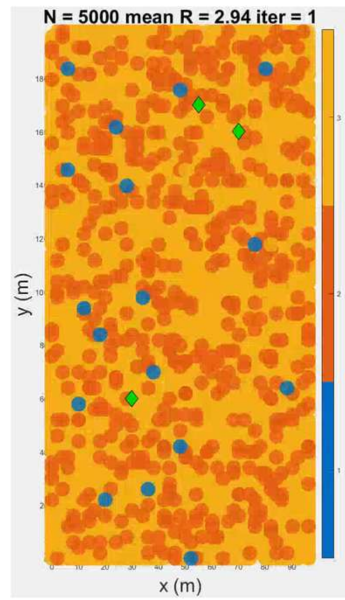
Georgia Tech
CREATING THE NEXT

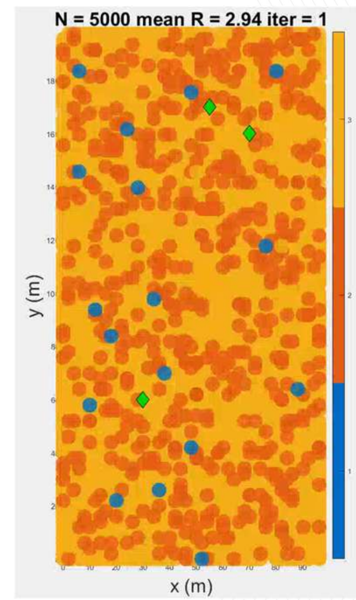
Algorithms for Autonomous Radiological Source Search

- Simulation results:
  - 100m x 200m search area
  - Building data from Open Street Maps
  - Buildings modelled as solid prisms with arbitrary absorption coefficients.
  - Attenuation modeled using simplified transport model:

Beer-Lambert Law

$$\mu = \mu_b + \sum_{s=1}^{r} \varphi_s \left(\frac{r_d}{d_s}\right)^2 e^{-\beta_{sd} d_s}$$

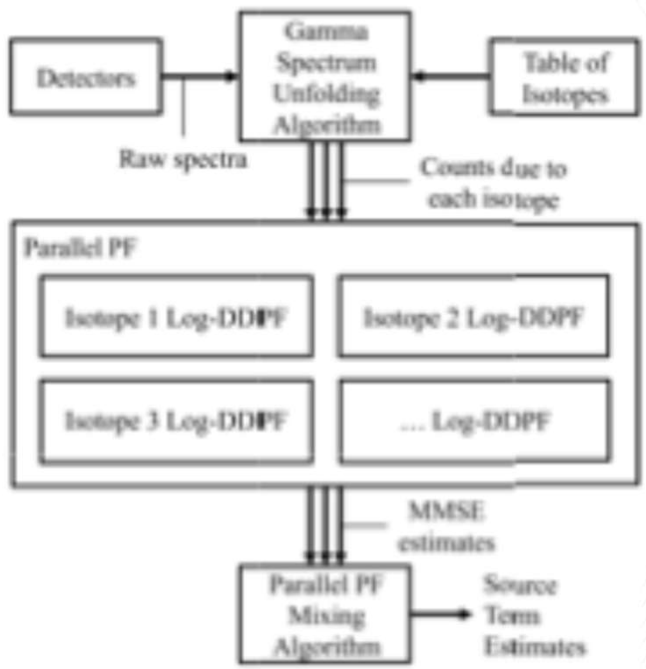




Kemp *et al*, IEEE TNS, 2023.

Algorithms for Autonomous Radiological Source Search

- Extension to **multi-isotope case** requires **spectrum unfolding** step and use of **multiple parallel particle filters**
- Detector data transformed into **counts from each isotope** using spectrum unfolding algorithm
  - Particle filter run for each isotope in table
- Particle filter **mixing algorithm** used to determine:
  - How many sources of which isotope
  - Strength(s)
  - Location(s)



Kemp *et al*, IEEE TNS, 2024.

Georgia Tech
CREATING THE NEXT

Algorithms for Autonomous Radiological Source Search

- Experimental Results
  - **Ground robot equipped with Kromek Sigma-50 CsI(Tl) scintillator**
  - **Search area:** 12m x 4m
  - **17 obstacles**
    - 2 bricks each
  - **45 measurements** taken using with 2-minute dwell time.
  - Unique absorption coefficients found for each isotope.

Kemp *et al*, IEEE TNS, 2024.

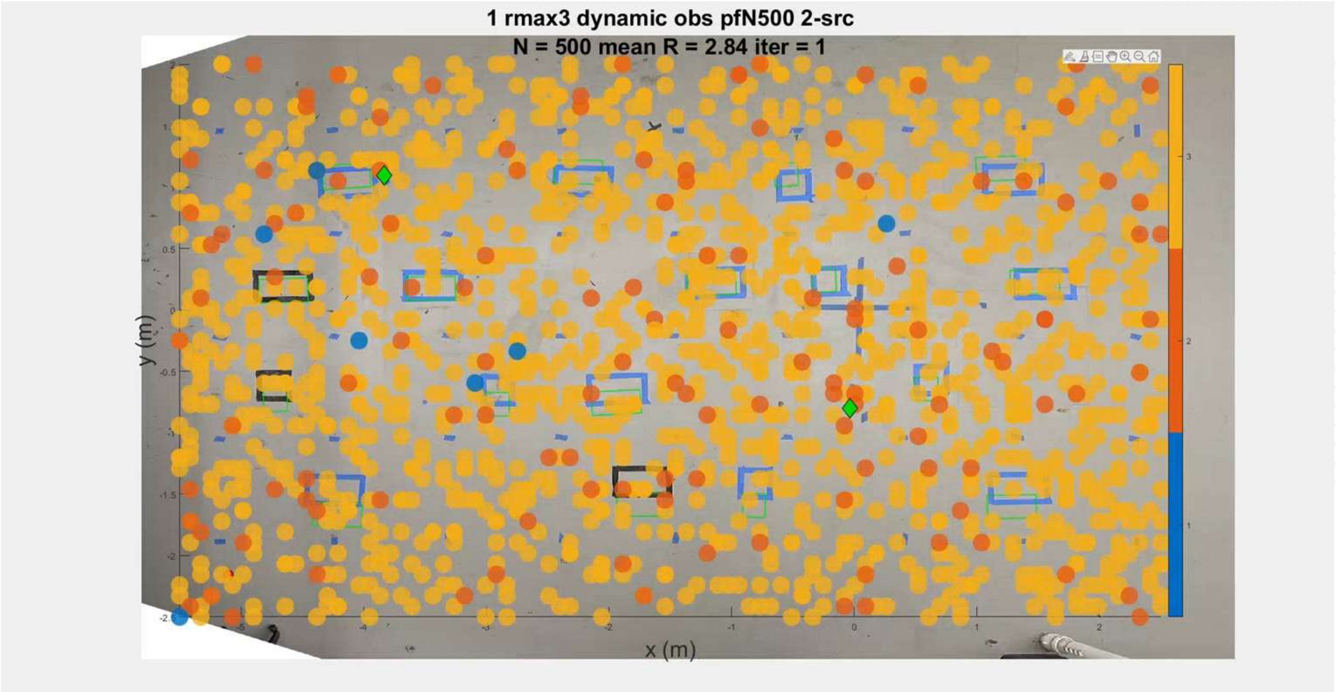
Georgia Tech
CREATING THE NEXT

Algorithms for Autonomous Radiological Source Search

Cs-137 @ 24.69 mCi (Top Left)
Cs-137 @ 0.152 mCi (Bottom Right)

Results:

- **Spatial error: 4.6 cm (.0074%)**
- **Strength Error: <1%**



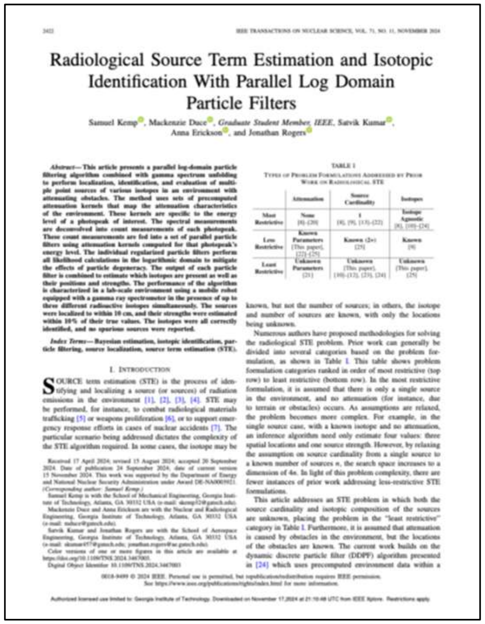
Kemp *et al*, IEEE TNS, 2024.

Algorithms for Autonomous Radiological Source Search

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 70, NO. 11, NOVEMBER 2023

Real-Time Radiological Source Term Estimation for Multiple Sources in Cluttered Environments

Samuel Kemp, Satvik Kumar, Craig Bakker, *Member, IEEE*, and Jonathan Rogers



IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 71, NO. 11, NOVEMBER 2024

Radiological Source Term Estimation and Isotopic Identification With Parallel Log Domain Particle Filters

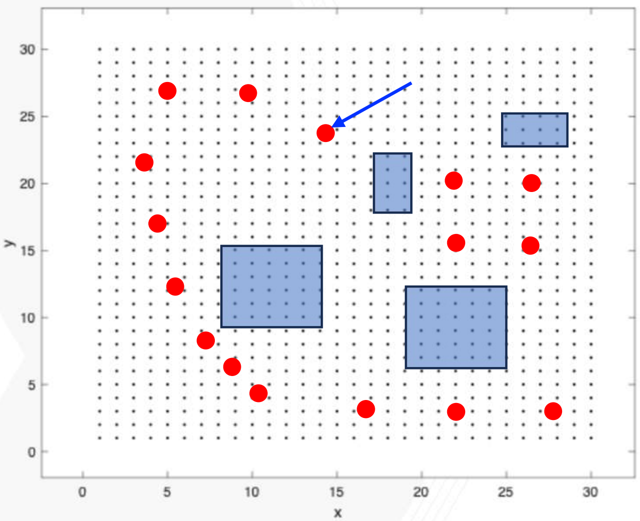
Samuel Kemp, Mackenzie Duce, *Graduate Student Member, IEEE*, Satvik Kumar, Anna Erickson, and Jonathan Rogers

S. Kemp, S. Kumar, J. Rogers, C. Bakker, “Real-Time Radiological Source Term Estimation for Multiple Sources in Cluttered Environments,” *IEEE Transactions on Nuclear Science*, Vol. 70, No. 11, 2023, pp. 2406-2419.

S. Kemp, M. Duce, S. Kumar, A. Erickson, J. Rogers, “Radiological Source Term Estimation and Isotopic Identification with Parallel Log Domain Particle Filters,” *IEEE Transactions on Nuclear Science*, Vol. 71, No. 11, 2024, pp. 2422-2431.

Georgia Tech
CREATING THE NEXT

More Recent Work – Optimizing Measurement Locations



Black points represent possible source locations (900 points)

Red points are possible measurement locations (15 points)

Blue rectangles are obstacles

Attenuation kernel matrix is 15 x 900 – represents attenuation between each source and measurement point

Example path between source point and measurement point shown in **blue arrow** – attenuation along this path is entry of kernel matrix

- Main benefit of GT's approach lies in discretization of STE problem – allows pre-computation of attenuation "kernel matrix"
  - Quantifies attenuation between all possible source locations $\vec{s}$ and all possible measurement locations $\vec{m}$
  - Kernel matrix can be computed using complex computational tools offline, then stored for use online

$$\vec{m} = A\vec{s}$$

Vector of all possible measurement points

Vector of source strengths at each point in source grid

Attenuation kernel matrix

Georgia Tech
CREATING THE NEXT

More Recent Work – Optimizing Measurement Locations

- Suppose we have 100 possible measurement locations, but we only have time to visit 10
  - Then we must find the 10 measurements that provide us with the most information
- Problem is then to find the submatrix formed from 10 rows of *A* that results in <u>best-conditioned inverse problem</u>

Full Inverse Problem (all 100 measurements)

$$\vec{m} = A\vec{s}$$

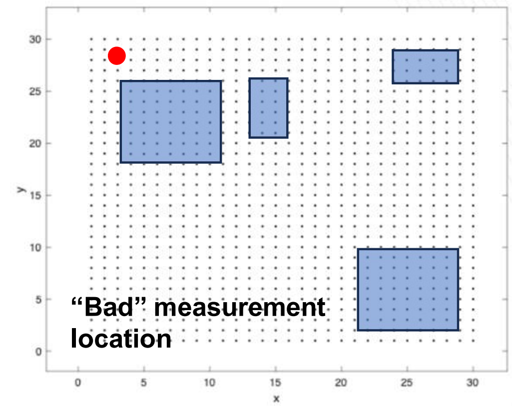
- $\vec{m}$: Vector of all possible measurement points
- A: Kernel matrix
- $\vec{s}$: Vector of source strengths at each point in source grid

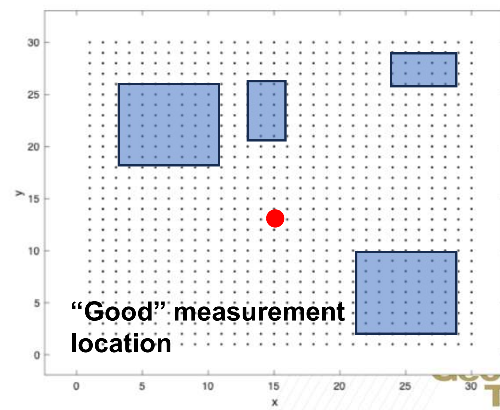
Reduced Inverse Problem (formed from "best" 10 measurements)

$$\vec{m}^* = A_{opt}\vec{s}$$

- $\vec{m}^*$: Vector of 10 best measurement points
- A_{opt}: Reduced kernel matrix formed from 10 rows of *A*
- $\vec{s}$: Vector of source strengths at each point in source grid

Example: "Good" and "Bad" Measurement Locations in Cluttered Environment





More Recent Work – Optimizing Measurement Locations

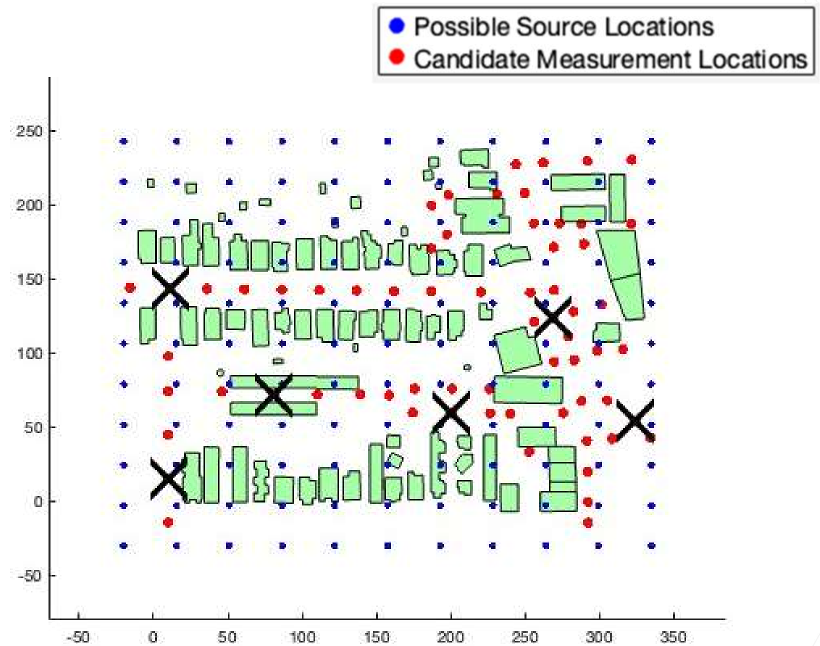
Stable rank of *A* matrix provides indication of how well-conditioned an inverse problem is.

$$Stable\ Rank = \frac{\|A\|_F^2}{\|A\|_2^2} = \frac{\sum_{i=1}^{\min\{m,n\}} \sigma_i^2(A)}{\sigma_{max}^2(A)}$$

Finding best measurement locations

means that we…

Find rows of *A* (submatrix) that provides the highest stable rank.



Black X's are the best 6 measurements out of all candidate measurement locations.

Drones for Inspection and Non-Destructive Testing

Funded by DOE (DE-SC0022680), collaboration with Sandia National Laboratories

NDT for Difficult-to-Reach Objects

*We commonly **expose personnel to more risk** during inspections than is necessary, given current state-of-the-art in robotics.*

Georgia Tech
CREATING THE NEXT

NDT for Nuclear Power Plant Monitoring

- Nuclear power plants involve a lot of large, concrete structures (cooling towers, containment units)
- These structures are relied upon for safe operations in case of extreme operational or environmental events (Tcherner et al, 2017)
- Many nuclear power plants are aging

Georgia Tech
CREATING THE NEXT

Drones for NDT of Infrastructure

Skygauge Ultrasound NDT Drone

Voliro Ultrasound NDT Drone

Elios Ultrasound NDT Drone

Interesting…but not efficient for large structures!

Georgia Tech
CREATING THE NEXT

Drones for NDT of Infrastructure

- New NDT technology is needed that **scans large-areas efficiently**
- Our UT scanner drone attaches to object being scanned using suction
- Deploys probe on 2-axis stage to scan 1 sq m

Krishnan et al., “Unmanned Aerial Vehicle Systems for Remote Testing and Inspection of Objects,” U.S. Provisional Patent Application No. 63/787,054, 2025.


DOE
SNL

Jonathan Rogers
Lockheed Martin Professor
School of Aerospace Engineering
jonathan.rogers@ae.gatech.edu