Source Term Estimation Using Multiple Isotopes in Atmospheric Samples

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Problem Statement

Xenon is a critical signature of nuclear explosions, but is also released by several harmless civilian nuclear processes. Screening out civilian signals is important to xenon effectiveness.

We report here a new Bayesian mathematical approach taking advantage of multiple isotopes, when detected, to further refine the time, location, and magnitude of the event. A new capability of this new method is the objective estimation of the likelihood of the release type. One immediate application of this new method is the screening out of civilian isotope signals.

We test this new analysis approach with a synthetic data set created using one simulated medical isotope type release forward transported to create multiple simulated 3-hour sample measurements at 39 stations.

The isotopes detected at the stations were considered compared to 33 release types, some only subtly different.

Bayesian Source-Term Model
for multiple isotopes

$$\underbrace{P(\vec{M}|D,I)}_{\text{posterior}} = \frac{\overbrace{P\left(D|\vec{M},I\right)}^{\text{likelihood}}\ \overbrace{P\left(\vec{M},I\right)}^{\text{prior}}}{\underbrace{P\left(D\right)}_{\text{normalizing constant}}}$$

Model ($\vec{M}$) uses the following release characteristics to describe a short-duration point release:

- Location (latitude and longitude)
- Elevation (set to ground level in this analysis)
- Start time and duration of release
- Magnitude of release (constant release rate)
- **Release type (characterized by the ratio of all isotopes to one "primary " isotope)**

The likelihood function uses synthetic data (D), subject matter expert information (I), and predicted concentrations (C) for all isotopes in each of the samples as follows:

$$\mathrm{P}\left(\mathrm{D}|\vec{M},I\right) \propto \exp\left[-\frac{1}{2}\sum_{\mathrm{i}}\frac{\left(\mathrm{D_i}-\mathrm{C_i}(\vec{M})\right)^2}{\sigma_{\mathrm{D,i}}^2+\sigma_{\mathrm{C,i}}^2}\right]$$

Data (D) are synthetic atmospheric samples with concentrations for 4 isotopes using 3-h collection times.

Simulated Release Event

- Hypothetical fission-based isotope production facility with 5 days irradiation and 24 h delay before release
- Atmospheric transport using Hysplit (NOAA) and nam12 meteorological data (NOAA)
- Modeled release (**MIPF_5d_24h**) was a 6-min puff containing
  - 1.03×10^{9} Bq of ^{131m}Xe (halflife of 11.84 days)
  - 1.48×10^{12} Bq of ^{133}Xe (halflife of 5.24 days)
  - 7.00×10^{10} Bq of ^{133m}Xe (halflife of 2.20 days)
  - 7.30×10^{11} Bq of ^{135}Xe (halflife of 0.381 days)
- Air samples generated for 39 locations (3-h duration)

Release Types Considered

The signals at the 39 sample locations were analyzed against 33 possible release types, including:

- **Nuclear Power Plants** – Published annual release values (UNSCEAR, 1988) for 5 BWR and 5 PWR plants
- **Nuclear Power Plant** – ORIGEN2.2 simulations of a generic BWR at 90, 180, 270, and 360 days after startup
- **Nuclear Explosion** – ORIGEN2.2 simulations of simple ^{235}U fission. Releases assumed at time of the explosion and delayed 1 hour, 1 day, and 10 days
- **Medical Isotope Production** – ORIGEN2.2 simulations of ^{235}U fission. Irradiation for 3, 4, 5, 6, or 7 days and release at 1, 3, or 24 h after the end of irradiation

Conclusions

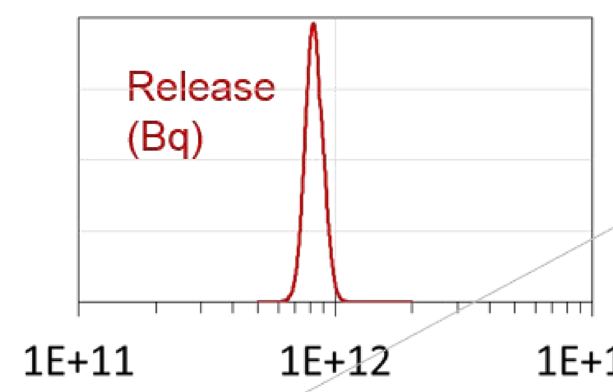
Only a synthetic experiment, and with modest station separation, but the results seem positive enough to explore further.

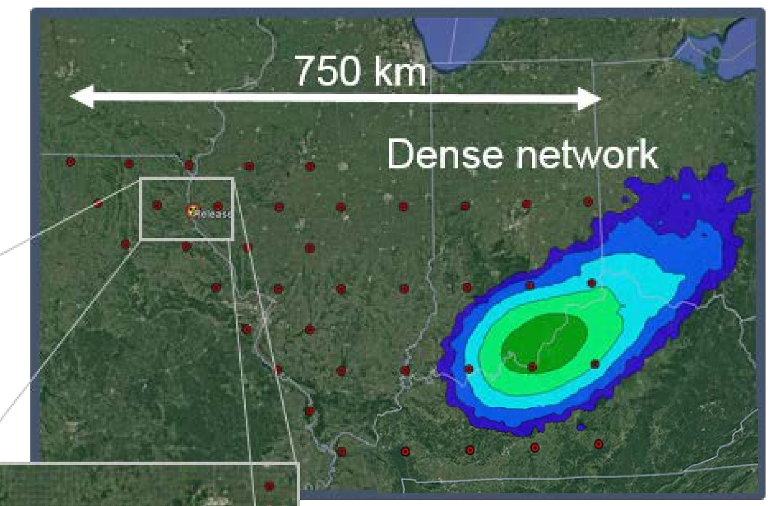
- All isotope combinations put highest probability on a medical isotope facility
- All cases with ^{135}Xe in addition to ^{133}Xe put highest probability on correct release type
- Cases with all values less that 0.0001 are not shown

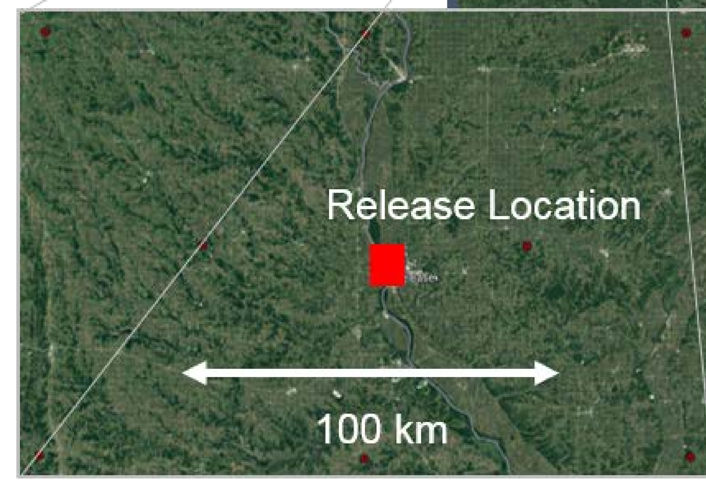
Results

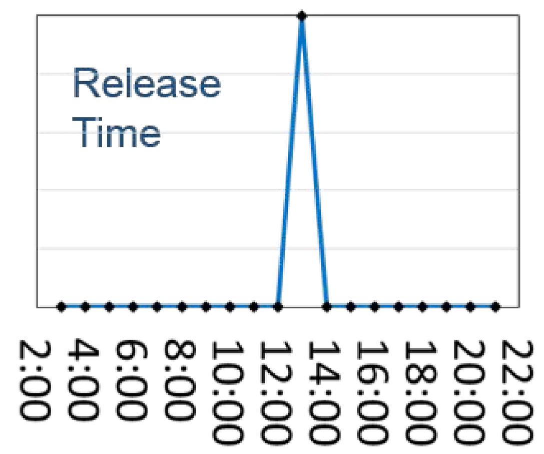
A. When all four isotopes are included:

- Location, time and duration are accurately determined
- Magnitude of release is low (but within a factor of 2)









B: Posterior Probability of Release Type for Isotope Combinations

Release Type	^{131m}Xe ^{133}Xe	^{133}Xe ^{133m}Xe	^{133}Xe ^{135}Xe	^{131m}Xe ^{133}Xe ^{133m}Xe	^{131m}Xe ^{133}Xe ^{135}Xe	^{133}Xe ^{133m}Xe ^{135}Xe	^{131m}Xe ^{133}Xe ^{133m}Xe ^{135}Xe
Fitzpatrick (BWR)	0	0.0729	0.0310	0	0	0.0183	0
Monticello (BWR)	0.0161	0	0	0	0	0	0
BWR_270d	0	0.0103	0.0077	0	0	0.0070	0
BWR_360d	0	0.0111	0.0058	0	0	0.0057	0
FD_24h	0.0315	0.0055	0	0.0003	0	0	0
MIPF_3d_01h	0.0018	0.0260	0.1026	0	0.0047	0.0126	0.0001
MIPF_3d_03h	0.0021	0.0277	0.0068	0.0001	0	0.0099	0
MIPF_3d_24h	0.0188	0.0505	0.0196	0.0039	0.0004	0.0340	0.0006
MIPF_4d_01h	0.0119	0.0418	0.0048	0.0015	0.0048	0.0001	0
MIPF_4d_03h	0.0136	0.0427	0.1229	0.0017	0.0083	0.1394	0.0038
MIPF_4d_24h	0.0557	0.0646	0.1328	0.0333	0.0743	0.1987	0.0789
MIPF_5d_01h	0.0417	0.0576	0.0002	0.0158	0.0003	0	0
MIPF_5d_03h	0.0448	0.0579	0.1481	0.0196	0.1296	0.1208	0.0565
MIPF_5d_24h	0.1008	0.0733	**0.1524**	0.1148	**0.3114**	**0.2064**	**0.3699**
MIPF_6d_01h	0.0869	0.0666	0	0.0748	0.0000	0	0
MIPF_6d_03h	0.0913	0.0693	0.0763	0.0845	0.1714	0.0506	0.0973
MIPF_6d_24h	**0.1249**	**0.0769**	0.0935	**0.1801**	0.2056	0.1177	0.2865
MIPF_7d_01h	0.1213	0.0751	0	0.1625	0	0	0
MIPF_7d_03h	0.1225	0.0749	0.0264	0.1645	0.0453	0.0150	0.0385
MIPF_7d_24h	0.1139	0.0736	0.0436	0.1427	0.0439	0.0495	0.0679
Any Reactor	0.0164	0.1162	0.0701	0	0	0.0454	0
Any MIPF	0.9521	0.8783	0.9299	0.9997	1	0.9546	1
Explosion	0.0315	0.0055	0	0.0003	0	0	0

Abstract

Algorithms that estimate the location and magnitude of an atmospheric release using remotely sampled air concentrations typically involve a single chemical or radioactive isotope. A new Bayesian algorithm is presented that makes discrimination between possible types of releases (e.g., nuclear explosion, nuclear power plant, or medical isotope production facility) an integral part of the analysis for samples that contain multiple isotopes. Algorithm performance is demonstrated using synthetic data and correctly discriminated between most release-type hypotheses, with higher accuracy when data are available on three or more isotopes.

References

This work:
Eslinger, PW, JD Lowrey, HS Miley, WS Rosenthal, and BT Schrom. 2019. "Source Term Estimation Using Multiple Xenon Isotopes in Atmospheric Samples." J Environ Radioact 204:111-116. doi:10.1016/j.jenvrad.2019.04.004

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