



## Inverse Modeling to Detect Illicitly Smuggled Materials in Containers

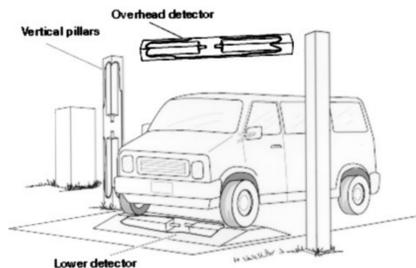
Wolfgang Bangerth, Marvin Adams, Nancy Amato, Jean-Luc Guermond, Guido Kanschat, Peter Kuchment, Jean Ragusa, Lawrence Rauchwerger  
Departments of Mathematics, of Computer Science, and of Nuclear Engineering, Texas A&M University

### Summary

To improve the chances of detecting nuclear material, for example HEU, smuggled in cargo containers or cars, all available data needs to be used simultaneously, not only by specifying a threshold on each individual detector reading. We present a framework in which we can compute the probability for false positives and false negatives. Such a framework also allows us to derive optimization problems that determine operating parameters that minimize the probability of false negatives subject to constraints such as cost, delay, etc. Furthermore, it allows us to evaluate the impact of proposed new detector concepts.

### Background

At ports of entry, cargo containers are subjected to a number of passive and active detectors for various kinds of radiation or non-radiation signatures:



Given detector readings  $d_i, i=1\dots N_d$ , the traditional way to operate is to set a threshold  $t_i$  for each detector beyond which a container is deemed suspect and may be subject to further scrutiny or manual inspection. These thresholds are typically determined empirically based on suspected quantities of HEU, suspected shielding, background radiation, etc.

A better approach would consider all measurements  $\mathbf{d}$  at once and determine a subset  $D_0$  of the space  $D$  of possible measurements within which measurements are deemed "safe" and outside of which they are considered suspicious. The traditional approach chooses  $D_0 = \{d_i < t_i, i=1\dots N_d\}$  but better choices are possible because the  $d_i$  are certainly correlated.

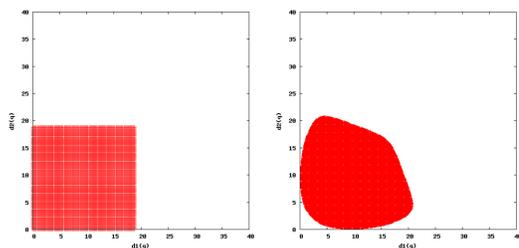


Fig.: Examples of domains  $D_0$  based on a priori thresholds  $t_i$  (left) and optimized to minimize the number of false negatives while keeping the number of false positives constant (right).

### Approach

If we know the internal composition  $q$  of a container (car, ...) then we can use radiative transfer computations and Monte Carlo simulations of detector responses to predict expected readings  $\mathbf{d}^*(q)$ . Using statistic models we can then also compute the probability that we measure  $\mathbf{d}$  when we expect  $\mathbf{d}^*(q)$ .

Let us assume that model  $q_0$  has no nuclear material, and models  $q_1\dots q_s$  are variants assumed to have different amounts of nuclear material with different amounts of shielding, in different locations, etc. Then we can compute probabilities  $P(\mathbf{d}|\mathbf{d}^*(q_s))$  for getting measurements  $\mathbf{d}$ :

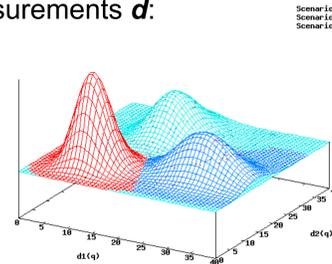


Fig.: Probabilities of getting detector readings  $\mathbf{d}$  for the base model  $q_0$  (left front) and variants  $q_1, q_2$  (left back, right front, both assumed to represent containers with HEU and therefore producing higher radiation readings in at least one detector).

If  $N_0\dots N_s$  are the numbers with which we expect to encounter container variants, then choosing  $D_0$  as the "safe" zone will produce

$$N_{\text{false negative}} = \sum_{s=1}^S N_s \int_{D_0} P(\mathbf{d}|\mathbf{d}^*(q_s))$$

$$N_{\text{false positive}} = N_0 \int_{D \setminus D_0} P(\mathbf{d}|\mathbf{d}^*(q_0))$$

false negatives and positives, respectively.

In practice, there are of course many different "base" configurations  $q_0^b$  and variants  $q_s^b, b=1\dots B$ . An adversary would choose that configuration and variant for which the probability to get through undetected (the container is a false negative) is maximized (i.e. he is the second player in a Stackelberg game). It is our goal to minimize the adversary's chances of doing so by choosing  $D_0$  appropriately:

$$\min_{D_0 \subset D} \max_{b=1\dots B, s=1\dots S} \int_{D_0} P(\mathbf{d}|\mathbf{d}^*(q_s^b))$$

The adversary's chances can be minimized by choosing  $D=\{\}$ , but at the cost that now all containers are false positives. We therefore have to add a constraint on the cost to deal with these false positives to the optimization problem:

$$\text{cost} \left( \sum_{b=1}^B N_0^b \int_{D \setminus D_0} P(\mathbf{d}|\mathbf{d}^*(q_0^b)) \right) \leq \text{budget}$$

### What does it take to make this work?

To compute solutions to this problem we need a number of things for which work is under way:

- Characterize possible container models  $q^b$  and realistic variants, as well as frequencies  $N^b$ . This requires obtaining realistic loading patterns and material parameters for possible contents of containers. Work on this is based on, for example, bills of lading.
- Accurate prediction of radiation levels to be expected from each model  $q_s^b$ . This poses significant computational challenges because of the complexity of modeling entire 40' cargo containers together with their contents; radiative transfer models for such objects will have both areas that are optically thick and optically thin. We use Texas A&M's Parallel Computational Transport (PCT) software to simulate radiative transfer processes.

- Accurate prediction of detector responses to given radiation level. This must take into account detector geometry and physics, standoff distance, etc. We use the MCNP code and realistic detector models for this.
- Characterization of various types of uncertainty such as shot noise, model uncertainty, numerical error, and background radioactivity levels. This is necessary to find realistic probabilities  $P(\mathbf{d}|\mathbf{d}^*(q_s))$ .
- Characterization of realistic constraints, for example in terms of delays (available from queuing network simulations), available workforce for manual searches, money, etc. All of these constraints need to be satisfied simultaneously.

### Going beyond

Beyond the points listed in the previous section, Texas A&M is working on a number of topics that go beyond the approach outlined above:

**Optimizing detector systems:** The framework above implied a fixed detection system. In practice, we would like to design a detection system optimized to the task of minimizing false negatives at fixed cost, or at minimizing cost at fixed number of false negatives. That is, if we have a set  $\{T\}$  of detector systems producing detector readings  $\mathbf{d}_T$ , then we would like to find the optimal detector system:

$$\min_{T \in \{T_i\}} \min_{D_0 \subset D_T} \max_{b=1\dots B, s=1\dots S} \int_{D_0} P(\mathbf{d}_T|\mathbf{d}^*(q_s^b))$$

$$\text{cost} \left( \sum_{b=1}^B N_0^b \int_{D \setminus D_0} P(\mathbf{d}|\mathbf{d}^*(q_0^b)) \right) + \text{cost}(T) \leq \text{budget}$$

In practice, we may not find the optimal detector system, but the framework at least allows us to compare two detector systems  $T_1, T_2$  to see which one is more reliable. Successful systems will add additional dimensions to the measurement space  $D$  not previously probed. Because it is the overlap of probability distributions  $P(\mathbf{d}|\mathbf{d}^*(q_0))$  and  $P(\mathbf{d}|\mathbf{d}^*(q_s))$  that limits our detection ability, we must strive to measure things that separate them. Examples for this are energy-resolved, time-resolved, or particle-type resolved detectors, coincidence counters, or active interrogation.

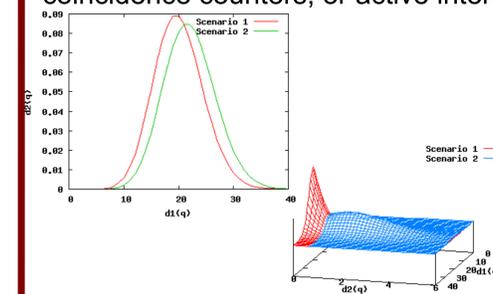


Fig.: Probabilities of getting a single gamma count reading  $d$  for a base model and a model with a small amount of HEU (left). Probabilities for the two models if we can measure count rates  $d_1, d_2$  outside the dominant HEU energy line and around the dominant line (right). Probabilities are now much better separated.

**Exploring imaging:** Ideally, detection would be based on 3d imaging of container contents. However, there is not enough data to do this. On the other hand, local or discrete tomography techniques may be able to determine some features of radiation sources inside containers, e.g. their location without resolving the strength or size.