Semi-empirical modeling to predict radiation detection performance for dynamic nuclear security

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ABSTRACT

To fully evaluate the performance of radiation detection systems in nuclear security use-case specific scenarios requires time and resource intensive test campaigns. Modeling and simulation tools can be used to reduce this burden; however, the available tools are limited when testing scenarios where relative motion between the radiation source and the detector system exists. If the radiation detection system under test contains a proprietary nuclide identification algorithm, then this further limits the usefulness of currently available software. On behalf of the Office of Nuclear Smuggling Detection and Deterrence (NSDD, NNSA NA-213), Los Alamos National Laboratory (LANL) has developed a tool, Detector Response for In-motion Virtual Experiments (DRIVE), that relies on a small set of measured data to produce use-case specific, time-series, spectral gamma detector and gross count neutron detector responses in formats that are compatible with vendor specific identification algorithms. The tool offers immense flexibility in the scenarios that can be rapidly simulated to offer order-of-magnitude estimates on the detection performance for the system. The adjustable parameters include relative speed and distance between source and detector, source strength scaling, background radiation scaling, number and location of detector modules, the ability to inject multiple source signatures in a single configuration, background suppression, background variation, sample rate, and number of trials to create (with statistical variation) for a given configuration. All parameters are modified through an easy-to-use user interface. The methodology of developing this tool, benefits, limitations, and assumptions are presented, along with several benchmark comparisons to real-world testing.

INTRODUCTION

In order to combat the illicit trafficking of nuclear materials, understanding the detection capabilities and limitations of available detection systems is critically important. Agencies interested in detection, deterrence, and interdiction of nuclear material smuggling execute time and resource intensive testing and evaluation campaigns to understand the detection systems' capabilities and determine proper Concept of Operations (CON-OPS). Due to the time and resources required to evaluate a system, modeling and simulation solutions could present a cost savings alternative, if done correctly. There are several unique problems that need to be addressed when simulating radiation detection equipment used by these agencies.

These issues include simulating an “in-motion" system where the detector response is time (position)-dependent as the source and/or detector are moving past each other, simulating the correct detector response for a given source/shielding configuration, and evaluating the various identification algorithms that are included with commercially available detection systems. Detector Response for In-motion Virtual Experiments (DRIVE)[1], developed at Los Alamos National Laboratory (LANL),

[1] Distribution of DRIVE is limited to U.S. Government Use Only, at the discretion of NSDD/NA-213. To request a copy of DRIVE, contact the author of this paper.

provides a unique solution to these challenges with an easy-to-use interface that rapidly generates time-series, spectral gamma, and gross-count neutron responses to user defined scenarios.

DRIVE simulations are based on a “basis set” of measured data, which are specific to the detector of interest, any sources of interest, and potentially include unique or scenario specific shielding on either the source (i.e. placing the source inside a shipping container, luggage, vehicle, etc.) or the detector system itself (i.e. accounting for the shielding introduced by mounting the detector in a discreet configuration). The basis set of data include a background spectrum, a static spectrum of all sources of interest, a static gross count measurement of any neutron producing sources of interest (if a neutron detector is to be included in the system), a horizontal response profile consisting of static measurements at intervals along the direction of travel, and the geometric information for the gamma and neutron detector modules. To further reduce the need for collecting experimental data, there are several available software packages that could be used to generate the static basis set measurements, provided the models are well validated.

The following list contains a number of intended uses of DRIVE to aid the end user in quickly providing order-of-magnitude estimates for the performance of spectroscopic systems intended for in-motion applications.

- Provide estimates of performance to guide the planning for testing and evaluation efforts.
- Provide rapid response estimates of performance to stakeholders for specific use-case scenarios.
- Extend the results of testing and evaluation efforts by predicting the performance for configurations not included in the physical testing.
- Evaluate the change in performance for increasing or decreasing the number of detector modules deployed in a modular detector system.
- Evaluate the change in performance when changing the geometric layout for modular detector systems.

SIMULATION METHODOLOGY

The overall simulation process is straightforward; first, user inputs are modified to create the desired trial configuration, and then these user inputs are used to produce simulated results that can be viewed in spectral analysis software such as PeakEasy[2] or InterSpec[3], or can be read into a vendor-specific replay tool to be analyzed by the identification algorithm. The simulation tool was developed using the C++ programming language. Figure 1 depicts the overall process flow for creating a simulated trial and evaluating the performance of the system for each simulated trial. While the process depicted in Figure 1 shows the process for a single detector module, DRIVE has the ability to accommodate modular detector systems and this process is repeated for all detectors in the configuration to get individual detector responses, and/or summed responses in “virtual detectors”[4]. At a high level, DRIVE produces simulated detector responses for user-defined dynamic scenarios by executing the following steps:

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[2] PeakEasy distribution is limited, and an account can be requested from https://peakeasy.lanl.gov.
[3] InterSpec is an open source software that can be downloaded from https://sandialabs.github.io/InterSpec/.
[4] A virtual detector in this sense is the combination of the spectral response from multiple detectors in the identification algorithm, in order to improve the signal-to-noise ratio and increase detection sensitivity.

i. The individual primitives are scaled based on the user inputs and integrated to produce time-series for each component[5].
ii. The individual components are summed together to create a threat-injected time-series.
iii. Poisson deviates are sampled for all channels of the spectrum for each data position along the time-series.

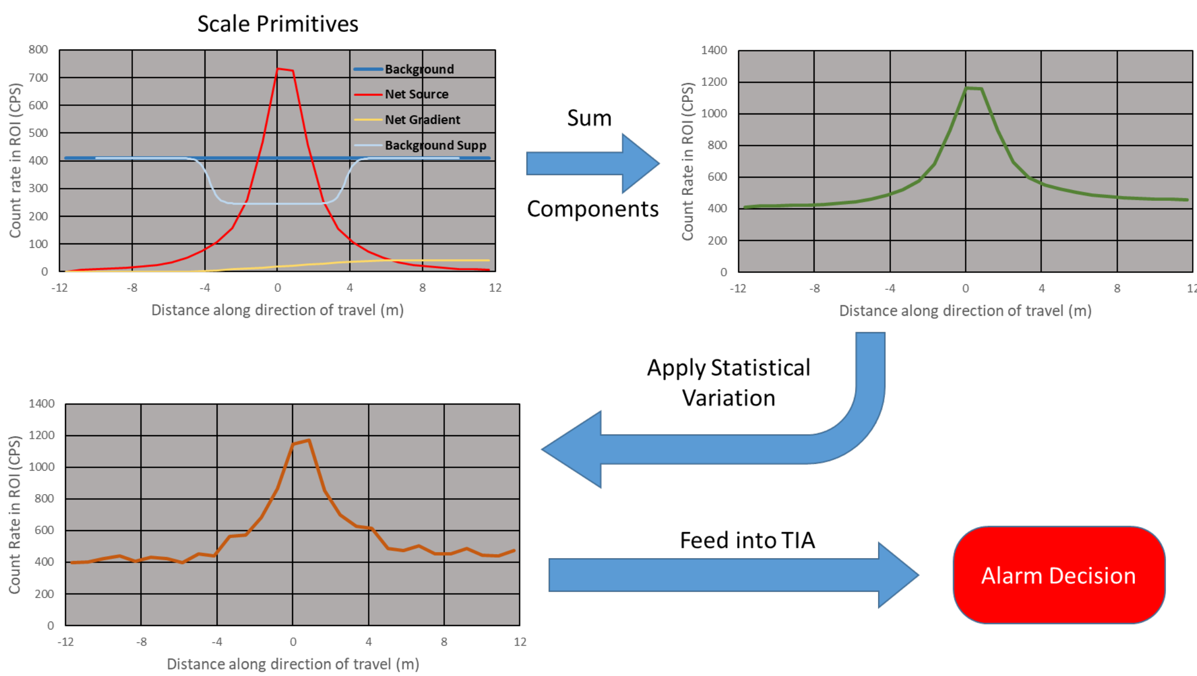

Figure 1. DRIVE simulation flowchart.

User Inputs

The user inputs can be broken down into two categories: those modifiable from the basic User Interface (UI), and those that can only be modified by an advanced user. The advanced inputs are stored in a configuration file, and contain detector/configuration specific information that can be loaded upon launching DRIVE. The basic inputs are those that are most commonly modified from one simulation to the next (see Figure 2).

[5] Scaling factors for special nuclear material includes self-shielding effects based on a compact metal source mass; scaling of all other source types is a straightforward multiplication factor based on the activity of the measured source.

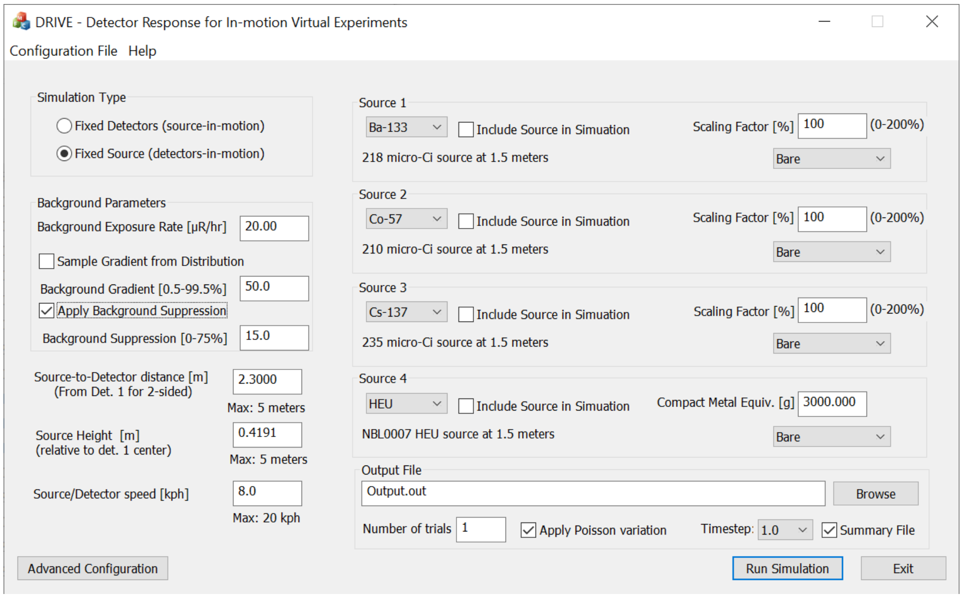

Figure 2. DRIVE user interface used to generate synthetic, dynamic trials

Running the Simulation

When the "Run Simulation" button is pressed, all inputs from the UI and configuration file are read into DRIVE. All of the source primitives that are included in the scenario are scaled according to their UI values and combined into a single spectrum to be injected into the trials; similarly, the background primitive is scaled according to the background exposure rate entered on the UI.

For each of the individual trials, the starting and ending locations are randomly selected, and each sample point is defined based on the speed and timestep of the synthetic data. Starting and ending locations for the source inject are approximately -10 meters and +10 meters, respectively, in the direction of travel. Additionally, 45 seconds of purely background data are added to the front and 15 seconds to the back end of each trial to provide any identification algorithm sufficient uncontaminated spectral data for its analysis.

For each detector defined in the configuration file for a given scenario, DRIVE takes the integral of the horizontal response profile (from the basis set of data) using the extended trapezoidal rule [3] to determine how much of the source term should be included in each sample point. The solid angle to the front of each detector face is used to correct for the geometry changes between the measured response profile and the synthetic detector response, using "A solid angle subtended by a rectangle at an arbitrary point" [1]. The equation that is evaluated using the trapezoidal rule for each sample point is shown in Equation 1, where g(x) is the cubic spline interpolation of the horizontal detector response profile, $\frac{\Omega}{\Omega_0}$ is the geometric correction factor using the solid angle for each detector in the scenario, and b-a is the distance traveled in each timestep.

$$\boldsymbol{\varepsilon} = \frac{\int_a^b g(x)\frac{\Omega}{\Omega_0}dx}{b-a} \qquad 1$$

For “detector-in-motion” simulations, background variation is an important real-world phenomenon that could adversely impact the identification algorithm, resulting in an increase in false alarms or decrease in sensitivity. In the simulations, the amount of background gradient will either be randomly sampled from distribution of measured background variation, or will be defined by the user. Once the amount of background variation is determined, the background variation will be applied from -5 meters to +5 meters and will then remain at the new background level for the remainder of the trial. The background gradient will be applied as a linear function over 10 meters with the increase (or decrease) in count rate coming from a NORM primitive that was measured using common NORM.

Background suppression is another known real-world phenomenon encountered when scanning large vehicles. Depending on the identification algorithm, a reduction in the background radiation signature, localized to the vehicle/item of interest, could increase, decrease, or have no effect on the signal from a threat source that is required to reach the alarm threshold. If the user chooses to include background suppression, then they specify a percent of the background that is reduced and the background signal will be reduced from approximately -5 meters to +5 meters. The specified suppression percent is the total suppression of the entire spectrum, however it is applied with some energy dependence so that more suppression is applied at low energy, based on real-world measurements of suppression.

Once all components of each synthetic trial have been generated, they are combined at each sample point to produce a single spectrum for each detector in the scenario. For each spectrum, a random number generator produces a Poisson deviate for each channel to give statistical variation to the spectra.

Once the trials are created inside the software, they need to be written to the appropriate output files. The N42.42 ANSI Standard [2] defines the fields and formats for the .n42 file that is a standard file type used for the output of radiation measurement instruments that are used for homeland security applications, however there is a lot of room for interpretation in the details and there is some variation from one vendor to another. In order for the output files of the simulation to be used in a vendor-specific replay tool, it is often necessary to match that vendors file format exactly. For this reason, DRIVE includes in the advanced user options several different output file types that are formatted specifically to work with certain vendor’s replay tools. For multiple trials of the same configuration (with statistical variation from one trial to the next), the files are appended with a unique number to distinguish one from another. When writing the output files, it is important to appropriately combine the responses from the physical, individual detectors into the virtual detectors that are defined in the advanced user inputs. These virtual detectors allow the algorithm or analyst to view the combined response of the entire array of detectors, or a subset of those detectors.

ASSUMPTION AND LIMITATIONS

The biggest limitation to the simulation methodology presented here, is that for configurations other than a bare source, the shielding is assumed to be uniform in all directions. There is no mechanism in place to account for streaming paths or for varying path lengths through a shield. If the shielding is fixed in relation to the detector array, then the measured profile response will account for that in the cubic spline interpolation, with the assumption that the shielding is similar for all detectors in the array.

While DRIVE provides the user lots of flexibility in varying parameters, the basis set of measurements should be collected with the detectors in a configuration and environment that's as close to the expected use-case as possible. The more that geometric parameters deviate from the measured dataset, larger discrepancies should be expected. Using the solid angle ratio to adjust for geometric deviations from the measured response profile does well to account for small variations, but it does not account for effects such as low-angle scattering, path lengths through the detector volume, and photons entering the sides or top/bottom of the detectors. As the deviations from the measured data increase, these limitations are more prevalent in the results.

Since DRIVE was developed with an intention of predicting limits of detection for a given scenario, high-flux effects such as pulse pileup and other high deadtime effects are not included.

RESULTS AND DISCUSSION

Benchmarking

To ensure that the simulated results accurately predict the time-series, spectral detector responses, several benchmark test cases were measured and compared to the simulated results. The results of these benchmarks showed very good agreement between the simulated and measured data, with larger discrepancies appearing in those cases where more complex geometry and shielding were present. Figure 3 shows one such comparison where the time-series response is compared between measured and simulated data. Figure 4 shows the spectral comparison at a single time step as the detector system moves past a source located in the trunk of the vehicle.

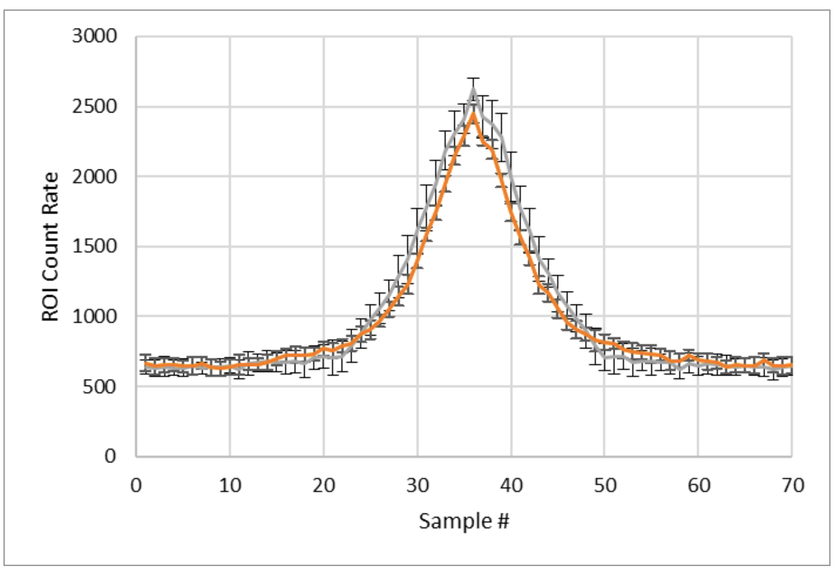

Figure 3. Comparison of measured data to simulated data, looking at the time-series gross counts within an energy region corresponding to the target isotope. For this simulation, one sample represents one-second of data.

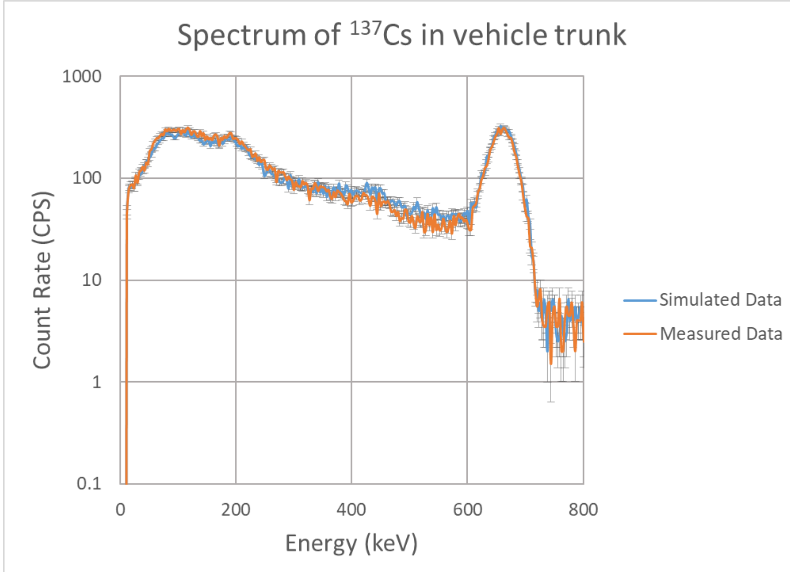

Figure 4. Spectral comparison at one time-step for a simulated run in which the source was located in the trunk of a vehicle as the detector system moved past.

DRIVE Use Cases

Three specific examples in which DRIVE was used to support stakeholder decision making are provided below.

Radiation Portal Monitor (RPM) Analysis: In this use case, DRIVE was used to determine how many, and in what virtual detector combination could sodium iodide detectors achieve the same sensitivity to highly enriched uranium (HEU), weapons grade plutonium (WGPu), and depleted uranium (DU) as the currently deployed gross counting plastic scintillator detectors used in vehicle RPMs. To perform this analysis, DRIVE was used to generate the synthetic detector response to a threat sources using an 8-detector, 12-detector, and 16-detector portal configuration. For each of the RPM configurations, the HEU, WGPu, or DU quantity was scaled to a target quantity, as determined by the stakeholder, and then sets of 20 trials were generated at two distinct speeds, and two background radiation levels. Each set of 20 trials was then fed into an isotope identification algorithm to determine the probability of identification (P_{ID}) for each scenario. Three RPM configurations, three sources, two speeds, and two background radiation levels times 20 trials each was a total of 720 trials that were rapidly generated by DRIVE to provide the stakeholder with the necessary information needed for making an informed decision moving forward. Figure 5 provides a depiction of the geometry of the 16-detector RPM used in this analysis.

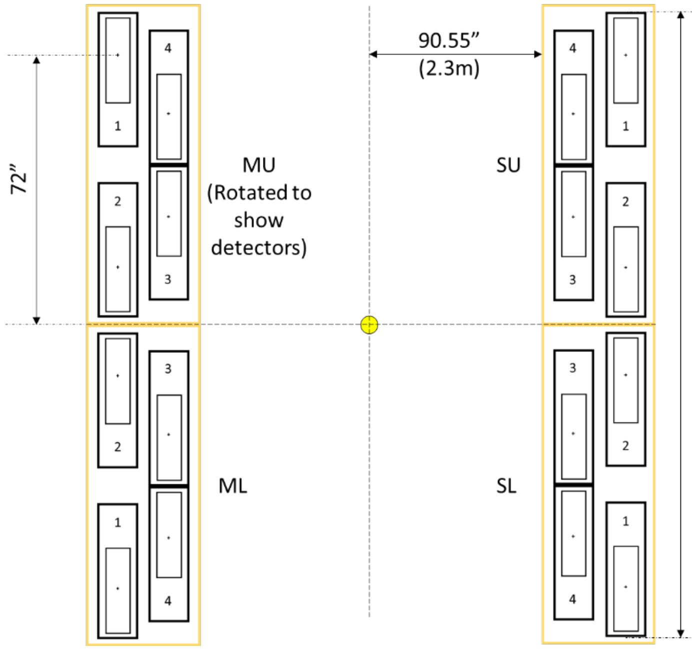

Figure 5. Configuration of 16-detector RPM used in DRIVE analysis

Carborne Analysis: In this use case, DRIVE was used to compare the performance of a rooftop mounted detection system to a cargo area (trunk) based system. Using HEU, WGPu, and a neutron source as the threat sources, DRIVE was used to determine the minimum detectable quantity (MDQ) at three distinct heights (ankle, hip, and shoulder) for a pedestrian scanning scenario. To determine MDQ, DRIVE is used to incrementally scale the HEU quantity until it reaches a point where the identification algorithm is able to reliably identify ^{235}U. Figure 6 shows two of the analysis results, the HEU results for the shoulder and ankle source locations. As expected, the rooftop mounted system was more sensitive than the cargo area system for the shoulder height, while the cargo area outperformed the rooftop system when the source was at ankle height. The DRIVE analysis for these configurations showing the relative sensitivity to HEU, WGPu, and a neutron source, along with other operational considerations for the intended deployment location allowed the stakeholder to make an informed decision about which configuration would better fit their needs.

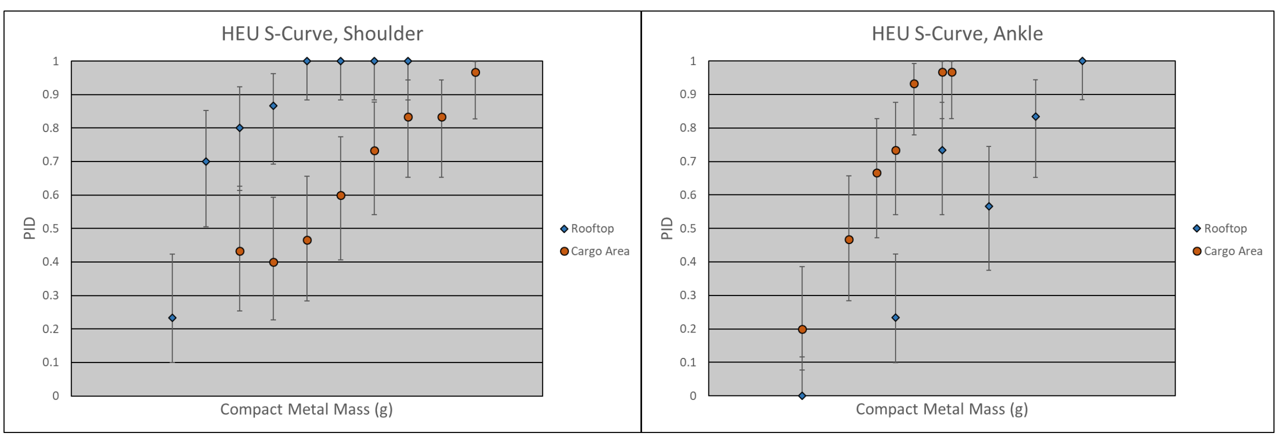

Figure 6. HEU S-curve analysis for shoulder (left) and ankle (right) height for the rooftop and cargo area mounting locations.

Mobile Detection System (MDS) Modular Analysis: For this use case, the stakeholder was interested in understanding how much sensitivity is gained when increasing the number of gamma modules for a system where multiple gamma modules are combined in the isotope identification algorithm (rather than treating each gamma module as an individual). For this analysis, DRIVE was used to determine the MDQ for HEU and WGPu, using a system with one, two, three, and four gamma modules, with the detectors mounted inside a van (see Figures 7 and 8). As expected, the sensitivity to both HEU and WGPu increased with more detector modules, but the sensitivity gains were greater for detecting HEU than they were for detecting WGPu. Table 1 shows the MDQ values for HEU and WGPu, normalized to the MDQ of the 1x gamma system. With this information, along with the cost of each additional gamma module, the stakeholder is able to perform a cost-benefit analysis of the increasing modularity of the radiation detection system.

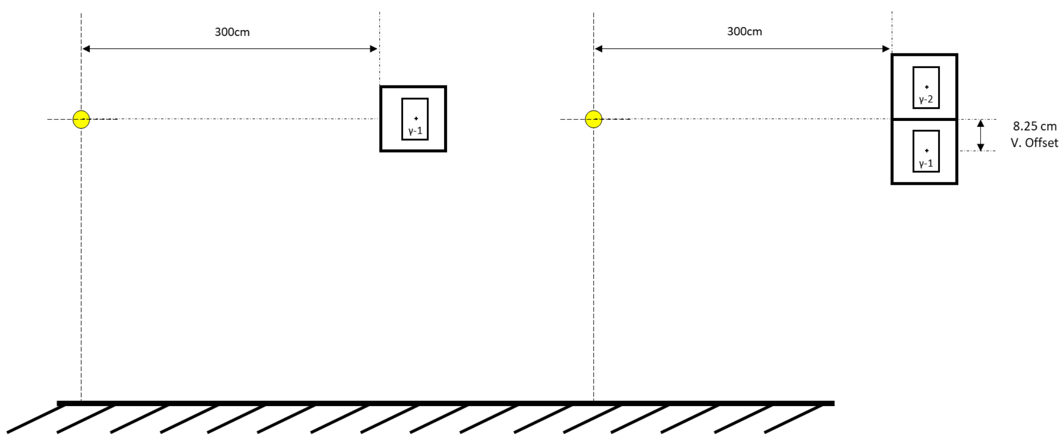

Figure 7. 1x and 2x gamma module simulation geometry.

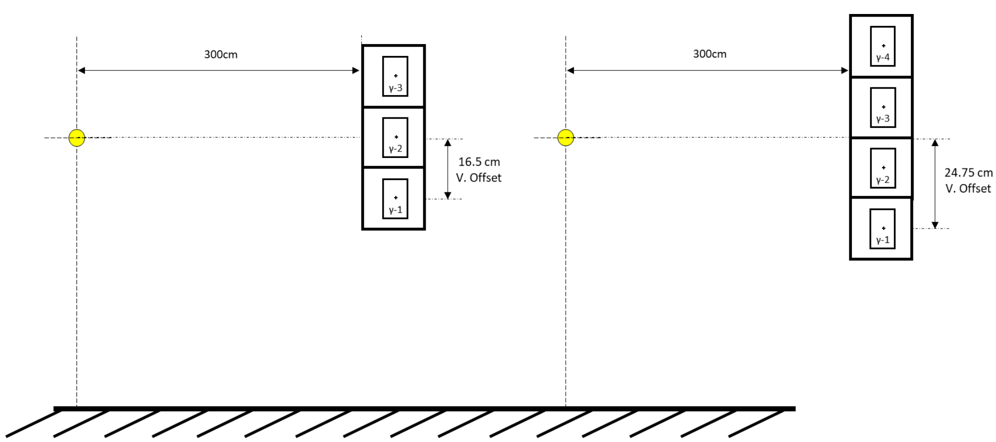

Figure 8. 3x and 4x gamma module simulation geometry.

Table 1. Normalized MDQ values for HEU and WGPu using 1, 2, 3, and 4 gamma module detection systems

Material	1x Gamma	2x Gamma	3x Gamma	4x Gamma
HEU	1.000	0.425	0.350	0.200
WGPu	1.000	0.538	0.462	0.385

Conclusion

The results show that using a semi-empirical modeling tool can accurately provide an estimate of the spectral, time-series response of a detector system used for in-motion applications. DRIVE was developed to give the user as much flexibility as possible in modularity, geometry, source scaling, speed, and intended use-case. DRIVE has been shown to quickly provide accurate order of magnitude estimates of detector performance and has been used to support stakeholder decision making for various applications of interest, without the need for an expensive and time consuming test campaign or a computationally heavy simulation.

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