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Numerical modeling of nonintrusive inspection systems

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ABSTRACT

A wide variety of nonintrusive inspection systems have been proposed in the past several years for the detection of hidden contraband in airline luggage and shipping containers. The majority of these proposed techniques depend on the interaction of radiation with matter to produce a signature specific to the contraband of interest, whether drugs or explosives. In our role as diagnostic specialists in the Underground Test Program over the past forty years, L-Division of the Lawrence Livermore National Laboratory has developed a unique expertise in the combined numerical and experimental modeling of these types of systems. Based on our experience, we are convinced that detailed numerical modeling provides a much more accurate estimate of the actual performance of complex experiments than simple analytical modeling. Furthermore, the construction of detailed numerical prototypes allows experimenters to explore the entire region of parameter space available to them before committing their ideas to hardware. This sort of systematic analysis has often lead to improved experimental designs and reductions in fielding costs. L-Division has developed an extensive suite of computer codes to model proposed experiments and possible background interactions. These codes allow us to simulate complex radiation sources, model 3-dimensional system geometries with "real world" complexity, specify detailed elemental distributions, and predict the response of almost any type of detector. In this work we will present several examples illustrating the use of these codes in modeling experimental systems at LLNL and discuss their potential usefulness in evaluating nonintrusive inspection systems.

1. INTRODUCTION

The increasing technological sophistication of criminal elements in our society over the past decade has made port and airline security a major problem. Recent drug busts at port facilities and acts of sabotage directed against the aviation community have demonstrated a growing awareness among would-be smugglers and terrorists of the design and deployment of contraband detection systems. At present, security officials are concerned primarily with relatively common items of contraband such as drugs, weapons, and conventional explosives, but we may someday be forced to deal with more exotic and dangerous contraband such as special nuclear materials and even fully assembled nuclear devices. Interdicting this contraband will be a massive problem requiring cooperative efforts between the private sector and many different agencies of the federal government. A broad range of technologies, many as yet undeveloped, will be necessary to counter these threats to our security and render attempts at smuggling and sabotage ineffective.

A variety of nonintrusive inspection systems have been proposed over the past several years for the detection of hidden contraband in airline luggage and shipping containers. Many of these systems have been discussed at recent conferences on cargo inspection technologies and aviation security.^{1,2} The majority of these proposed techniques depend on the interaction of radiation with matter to produce signatures specific to the contraband of interest, whether illegal drugs or explosives. Almost without exception, these schemes have been based on simplified physical models which assume straight-line radiation transport and single interactions between the probe particles and the container of interest, assumptions which we have found rarely prove true in the world outside the laboratory.

In our role as diagnostic specialists for the Underground Nuclear Test Program, L-Division of the Lawrence Livermore National Laboratory has developed a unique expertise in the combined numerical and experimental modeling of these types of systems. Based on our experience, we are convinced that numerical modeling provides a much more accurate estimate of the actual performance of complex experimental systems than does simple analytical modeling. Furthermore, the construction of detailed numerical prototypes allows system developers to quickly explore the full parameter space available to them before committing their ideas to hardware. This sort of systematic analysis has often lead to improved experimental designs at LLNL and reductions in overall system development costs. In this work we will present several examples illustrating the use of numerical modeling in prototyping experimental systems at LLNL and discuss its potential usefulness in evaluating nonintrusive inspection systems.

2. NUMERICAL TECHNIQUES

Over the years, a wide variety of radiation transport codes have been developed by researchers at LLNL and elsewhere. However, because they were typically written for older, slower computers with relatively small memories, these codes were frequently forced to compromise between "good physics" and the practical need to solve problems in a reasonable length of time. As a result, most of these earlier transport codes suffered from serious inaccuracies or other flaws which limited their usefulness as modeling tools.

During the early 1980's, researchers at LLNL set out to develop a modern, full-featured radiation transport code which could exploit the power of the newer, high-speed Cray computers then coming on line. The result, released to the local community in the mid-1980's, was COG (so named after an old-English slang term referring to "a trick of the dice").³ COG is a detailed, high-resolution Monte Carlo neutron and photon transport code capable of providing accurate answers to complex deep-penetration (or shielding) problems. Unlike many of its predecessors, COG is free of the physics compromises and approximations traditionally used in radiation-transport calculations. COG is fully three-dimensional, uses point-wise-correct cross-sections and exact angular scattering functions, and provides the user with a full range of statistical biasing options to speed up problem solving. Problem geometries can be set up manually using simple but powerful constructs (more than 30 complex pseudo-surfaces such as boxes, spheres, cylinders, and cones are included in COG's geometry package as elementary types) or developed using CAD tools and then transformed automatically into the proper input format. System components can be visualized in both cross-sectional and perspective views to assure their fidelity and complex geometries can be debugged on a standard Macintosh workstation. COG allows users to score the results of a simulation using either built-in detector types or user-written detector packages linked in at run time.

The accuracy of a simulation in COG is limited only by the accuracy of the data that it uses. The code is currently capable of accessing either of two well-known cross-section databases to determine the probability of a particle interacting with the medium through which it is transported. One is LLNL's Evaluated Nuclear Data Library (ENDL-90), and the other is the Evaluated Nuclear Data File (ENDF/B-V). COG's accuracy and reliability have been proven through extensive benchmarking on radiation shielding and criticality problems relevant to recent LLNL programs.⁴

Several major enhancements to COG are currently being planned. Primary among these will be the addition of electron transport. In its present form, the code correctly accounts for the production of secondary electrons, but cannot follow their subsequent trajectories (a knowledge of these trajectories would greatly enhance COG's ability to model detector responses). The transport formalism used by the EGS electron transport code⁵ will be used as a model to incorporate this capability into COG. In addition, the code is currently being adapted for use on the latest generation of Unix-based workstations including those produced by HP, Sun and IBM. COG will soon be released as public-domain software, making it available to any user with the requisite computational resources.

3. MODELING EXPERIMENTAL SYSTEMS

The development of reliable techniques to simulate the interaction of radiation with matter in complex experimental situations has been essential to the success of the Underground Nuclear Test Program and laboratory physics programs at LLNL. Recent applications of numerical modeling in these areas are highlighted below.

3.1 Underground nuclear test diagnostics

The primary impetus to develop more powerful numerical modeling tools at LLNL came from the Underground Nuclear Test Program. As the number of nuclear tests conducted each year began to decline in the early 1980's, the complexity of the tests increased rapidly, with scientists working to maximize both the quantity and quality of diagnostic data obtained on each event. Pre-shot numerical simulations have been a key asset in assuring a high rate of data return from recent events.

Two computer-generated, high-resolution, perspective views from the numerical simulation of the diagnostics canister for a recent underground nuclear test are shown in Figures 1a and 1b. In a typical test, specialized detectors mounted in protective steel enclosures view the radiation from an exploding nuclear device suspended just below the canister through numerous line-of-sight pipes (evacuated steel tubes) aimed at various parts of the device. In order to assure the return of clean, high-quality data from each experiment, it is essential that the diagnostics canister be designed to minimize detector crosstalk and unwanted backgrounds due to scattered radiation from adjacent collimators and pipes. This is usually accomplished by isolating the experiments from one another using various shielding materials such as solid iron, lead sheathing, and iron-rich sand (included in the calculations, but not shown in the figures). Detailed numerical simulations which exploit the power of

modern, high-speed computer systems are essential to the accurate analysis of complex, deep-penetration, multiple-scattering problems such as these. Simple analytical calculations are simply inadequate.

The flexibility of the numerical modeling formalism provided by COG allows us to predict both detector responses and background count rates at virtually any location within a diagnostics canister. As an example of the latter, composite predictions for the anticipated neutron and gamma backgrounds at an elevation of $\approx 210''$ above the device plane due to scattering from the various lines-of-sight in the diagnostics canister discussed above are shown in Figures 1c and 1d, respectively (the various contributions would normally be plotted separately, but have been overlaid here for convenience). On this particular event, the predictions for detector response agreed with experimental measurements to within 20% and the much more complicated background signals were estimated to within a factor of 2.

3.2 Laboratory nuclear physics experiments

We have recently begun a series of laboratory neutron capture experiments of interest to both the weapons program at LLNL and the field of nuclear physics in general. These experiments are designed to measure both the energy and angular distributions of gamma rays produced by the radiative capture of 14 MeV neutrons incident on ^{63}Cu and ^{239}Pu targets. The measurements will be used in predicting neutron-induced backgrounds in underground nuclear test experiments and to validate direct and semi-direct theoretical models for radiative neutron capture. The primary concerns during the design of the experiment were estimating the neutron-induced background in the gamma spectrometer itself and mitigating the radiation dose to people near the experimental area (note that this problem addresses many of the same questions that would arise in deploying a radiation scanning device in a heavy-traffic location such as an airport terminal or commercial harbor).

A computer-generated, perspective view from the numerical simulation of the experiment station is shown in Figure 2c. This model, which includes the gamma spectrometer and its surrounding area, was used to assess the adequacy of various radiation shielding schemes. Predictions of radiation dose rates made using this model have since been confirmed by direct measurement. In this case, the simulations allowed us to develop an inexpensive but effective shielding scheme so that we could obtain the necessary data at a reasonable cost without endangering other workers in the area.

A computer-generated, cross-sectional view of the gamma spectrometer itself (referred to as HEGRS for High-Energy Gamma-Ray Spectrometer) is shown in Figure 2b.⁶ HEGRS consists of a 28 cm x 30 cm NaI crystal enclosed in a plastic anticoincidence shield made of boron-carbon 408. Additional shielding was provided by iron, lead, and borated resin. The crystal and its shielding form a single unit which can be rotated around the target position. This model was used to predict neutron-induced backgrounds in the crystal (Figure 2c). As with the dose rate, these predictions have since been confirmed by direct measurement.

4. EVALUATING NONINTRUSIVE INSPECTION SYSTEMS

The design and implementation of nonintrusive inspection systems for the detection of hidden contraband or explosives in airline luggage and shipping containers presents many formidable problems. Systems which appear conceptually straightforward and promise to be highly effective during the design (and marketing) phase sometimes prove difficult to implement and often fail to perform up to initial expectations due to unforeseen complications. Given overall development costs which can easily run into millions of dollars for many of systems, this presents serious problems for developers and end-users alike. We have used detailed numerical simulations to assess the efficacy of several nonintrusive inspections systems recently proposed at LLNL prior to committing funds for the construction of actual mechanical prototypes. Two examples of this modeling are highlighted below.

4.1 Void detection in solid materials

The detection of voids or inclusions deep within solid materials is a challenging problem relevant to both contraband interdiction and nondestructive testing of materials. We have recently modeled several proposed techniques for detecting and characterizing voids located several centimeters below the surface of a solid. Figure 3a shows a computer-generated, cross-sectional view from the numerical simulation of one such scheme.⁷ In this model, a tightly collimated beam of 0.662 MeV gamma rays from a ^{137}Cs source is used to probe a thick target slab which has a small void located at a depth d (typically $\approx 2 - 4$ cm) below the surface. The Compton backscattered gamma rays are detected using a high-resolution, energy-dispersive detector fitted with a specially-designed collimation system. Although the geometry of this system appears to be relatively simple, it is still a deep-penetration problem in which multiple scattering can be expected to make a significant contribution; therefore detailed numerical simulations are essential to an accurate assessment of system capabilities.

Our initial COG simulations were aimed at predicting energy spectra for Compton-scattered photons and estimating the detected yields and background contributions due to multiple scattering for several baseline problems involving 0.662 MeV gammas incident on iron and wood target slabs with and without embedded voids. Typical spectra for iron and wood target slabs (without voids) are presented in Figures 3b and 3c, respectively. The rectangular peaks near 0.290 MeV correspond to the energy range accepted by the detector collimator (≈ 0.272 MeV - 0.306 MeV). The detected yield from the iron target was estimated to be $\approx 5.10\text{E-}08$ counts per second per photon in the incident beam with a multiple-scattering contribution of $\approx 40\%$. The corresponding yield from the wood target was predicted to be somewhat larger at $\approx 8.56\text{E-}08$ counts per second per photon in the incident beam with a multiple-scattering contribution of only $\approx 5\%$ (note that analytical calculations aimed at determining the multiple scattering contribution are all but intractable for this geometry).

As an example of our overall analysis of this system, the absolute spatial resolution of the proposed technique (*i.e.* its ability to resolve closely spaced objects) was estimated by running a series of simulations in which "structured voids" were used to mock up line resolution charts of various optical densities. The voids were modeled here as 2 mm x 2 mm x 1 cm rectangles containing grid structures simulating resolutions of 0.5 lp/mm to 2.0 lp/mm. The grid structures were centered 2 cm below the surface of the target slab. The predicted spectrum for the case of an iron target with a 0.50 lp/mm structured void (corresponding to an object resolution of 2.000 mm) is shown in Figure 3d. The grid structure is clearly visible in this spectrum. Figure 3e shows an expanded view of the energy region of interest convolved with a 1 keV (FWHM) Gaussian resolution function. The structure is still visible in the convolved spectrum, with an estimated contrast of $\approx 73\%$, implying that objects separated by ≈ 2 mm should be easily resolved in actual experiments. Additional simulations (not shown here) established the ultimate system resolution at ≈ 1 mm.

4.2 Luggage scanning with fast neutrons

We have recently used detailed numerical simulations to assess the performance of a proposed fast-neutron transmission inspection system for checked luggage.⁸ Computer-generated perspective and cross-sectional views of the system are shown in Figures 4a and 4b, respectively. In this model, a pulsed deuteron beam of energy ≈ 7 MeV is stopped in a thick Be target and generates a broad-spectrum neutron pulse ($\approx 0 - 12$ MeV) which is detected after passing through a piece of luggage by a plastic scintillator detector mounted in a boron-loaded, epoxy-resin housing. The neutron transmission as a function of time is used to infer the densities of hydrogen, carbon, oxygen, and nitrogen in the sampled volume. The measured densities can then be compared to known signatures for explosives or other contraband materials.

Preliminary results for the time-of-flight neutron spectra that one might expect from luggage with and without hidden explosives is shown in Figure 4c. Since the detector signal can be expected to include contributions from both transmitted neutrons and neutrons which have undergone one or more scatterings ($\approx 30 - 35\%$ of the total), the signal is *not* simply the source intensity times appropriate transmission factors. Note in particular that the predicted signal for a run with a suitcase carrying explosives is actually larger than that for a run with no luggage on the conveyor. This implies that in-scatter from the luggage is larger than out-scatter - a result that would never be obtained using simple straight-line attenuation models. This interference effect of neutrons arriving at the detector at different times due to interactions within the sampled volume will make the interpretation of the measured signals extremely challenging.

5. SUMMARY COMMENTS

The development of effective nonintrusive inspection systems for use in airline terminals and port facilities is clearly a challenging problem. We believe that detailed numerical simulations can be an extremely valuable tool in prototyping such systems. Many fundamental issues such as detection probability, false alarm rate, and rate of throughput, which previously could only be determined in an operational setting, can now be accurately (and objectively) estimated using powerful radiation transport codes such as COG. Numerical modeling allows system designers to optimize detection schemes for a given application, investigate possible masking or spoofing techniques, estimate radiation doses to system operators, and evaluate methods for interpreting signals. In short, we believe that numerical modeling can help designers to develop more effective systems in less time and often at a lower overall cost.

6. ACKNOWLEDGMENTS

We would like to thank R. Buck and E. Lent of L-Division for their contributions to the description of the radiation transport code COG provided in Section 2 of this work and for their continued agility in responding to the ever-changing demands of the numerical modeling community at LLNL.

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8. COLLECTED FIGURES

Figure 1a - High-resolution perspective view from the numerical simulation of a typical diagnostics canister for an underground nuclear test (some components have been omitted to show the experimental layout).

Figure 1b - High-resolution perspective view from the numerical simulation of a typical diagnostics canister for an underground nuclear test (close-up of experiments in typical canister bay).

Figure 1c - Predicted time-differential neutron flux at an elevation of $\approx 210''$ above the device plane due to scattering from various lines-of-sight (independent signals have been overlaid here for convenience).

Figure 1d - Predicted time-differential gamma flux at an elevation of $\approx 210''$ above the device plane due to scattering from various lines-of-sight (independent signals have been overlaid here for convenience).

Figure 2a - Low-resolution perspective view from the numerical simulation of the experiment station for LLNL neutron capture experiments (model used to assess the adequacy of radiation shielding schemes).

Figure 2b- Cross-sectional view from the numerical simulation of the gamma spectrometer used in LLNL neutron capture experiments (model used to predict neutron-induced backgrounds at crystal position).

Figure 2c- Predicted energy-differential neutron flux at HEGRS crystal position (spectra used to calculate neutron-induced backgrounds in LLNL neutron capture experiments).

Figure 3a - Cross-sectional view from the numerical simulation of a backscatter imaging scheme proposed for characterizing voids located below the surface of a solid (model used to assess system capabilities).

Figure 3b - Typical COG spectrum for an iron target slab (error bars represent $\pm 1 \sigma$); detector collimator aimed at a point 2 cm below the surface of the slab.

Figure 3c - Typical COG spectrum for a wood target slab (error bars represent $\pm 1 \sigma$); detector collimator aimed at a point 2 cm below the surface of the slab.

Figure 3d - COG spectrum for an iron target with a structured void representing an object resolution of 0.5 lp/mm (error bars represent $\pm 1 \sigma$); void centered at a point 2 cm below the surface of the slab.

Figure 3e - Expanded view of previous COG spectrum (solid line) convolved with a 1 keV (FWHM) Gaussian resolution function (dashed line).

Figure 4a - Low-resolution perspective view from the numerical simulation of a proposed fast-neutron transmission inspection system for checked luggage (model used to assess system capabilities).

Figure 4b - Cross-sectional view from the numerical simulation of a proposed fast-neutron transmission inspection system for checked luggage (model used to assess system capabilities).

Figure 4c - Predicted time-of-flight neutron spectra for luggage with and without hidden explosives (note that the signal for a run with a suitcase carrying explosives is actually larger than that for a run with no luggage on the conveyor).

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