Automated Variance Reduction Applied to Nuclear Well-Logging Problems

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INTRODUCTION

The Monte Carlo method enables detailed, explicit geometric, energy and angular representations, and hence is considered to be the most accurate method available for solving complex radiation transport problems. Because of its associated accuracy, the Monte Carlo method is widely used in the petroleum exploration industry to design, benchmark, and simulate nuclear well-logging tools. Nuclear well-logging tools, which contain neutron and/or gamma sources and two or more detectors, are placed in boreholes that contain water (and possibly other fluids) and that are typically surrounded by a formation (e.g., limestone, sandstone, calcites, or a combination). The response of the detectors to radiation returning from the surrounding formation is used to infer information about the material porosity, density, composition, and associated characteristics. Accurate computer simulation is a key aspect of this exploratory technique. However, because this technique involves calculating highly precise responses (at two or more detectors) based on radiation that has interacted with the surrounding formation, the transport simulations are computationally intensive, requiring significant use of variance reduction techniques, parallel computing, or both.

Because of the challenging nature of these problems, nuclear well-logging problems have frequently been used to evaluate the effectiveness of variance reduction techniques (e.g., Refs. 1–4). The primary focus of these works has been on improving the computational efficiency associated with calculating the response at the most challenging detector location, which is typically the detector furthest from the source. Although the objective of nuclear well-logging simulations is to calculate the response at multiple detector locations, until recently none of the numerous variance reduction methods/techniques has been well-suited to simultaneous optimization of multiple detector (tally) regions. Therefore, a separate calculation is typically performed for each desired detector response.

This paper summarizes recent work to apply and evaluate the effectiveness of deterministic-adjoint-based variance reduction methods, including a recently developed method for simultaneous optimization of multiple detectors, for two simple nuclear well-logging tool problems that have been widely used in the variance reduction literature. The computational effectiveness of the method for simultaneous optimization is also compared to the use of multiple, individually optimized simulations for these simple well-logging problems.

METHODS

Advanced, automated variance reduction methods that utilize approximate forward and/or adjoint fluxes to generate consistent source and transport biasing parameters for accelerating Monte Carlo simulations have been developed and implemented at ORNL for use in SCALE [5] and MCNP.[6] For accelerating Monte Carlo calculations of localized quantities (e.g., a detector tally), the CADIS (Consistent Adjoint Driven Importance Sampling) method,[7] which utilizes an approximate adjoint solution to determine consistent source and transport (weight windows) biasing parameters, is used.

Alternatively, for accelerating Monte Carlo calculations of either mesh tallies or multiple localized quantities (e.g., multiple detector tallies), the Forward-Weighted CADIS (FW-CADIS) method [8] is used. FW-CADIS utilizes an approximate forward solution to weight the source in an adjoint calculation such that the resulting adjoint importance function represents the importance of particles to achieving uniformly distributed Monte Carlo particles throughout the requested tally regions. The premise for the FW-CADIS method is that uniformly distributed Monte Carlo particles should roughly correspond to uniform statistical uncertainties in those regions. As implemented, the approximate forward and/or adjoint fluxes are generated by deterministic transport calculations from either the Denovo or TORT three-dimensional discrete ordinates codes. Because these methods involve the combined use of deterministic and Monte Carlo transport methods, they are referred to as “hybrid” methods.

The CADIS and FW-CADIS methods have been fully implemented and automated in the MAVRIC (Monaco with Automated Variance Reduction Using Importance Calculations) sequence,[9] being developed for public release in SCALE 6. The calculations performed for this paper were all done with MAVRIC.

DESCRIPTION OF THE ACTUAL WORK

The CADIS methodology was applied to representative models of a neutron porosity tool (problem 12 from the MCNP test set [6]) and a gamma-ray lithology-density tool [10] to demonstrate its effectiveness

for optimizing the calculation of the individual detector responses. Additionally, the newly developed FW-CADIS method was applied to demonstrate and evaluate its effectiveness for simultaneous optimization of multiple detectors (e.g., both near and far detector responses) in a single simulation. Previous work [4] has demonstrated the greater efficiencies associated with the CADIS methodology/implementation for individual detector responses for a representative nuclear well-logging tool, as compared to manual optimization and the use of the MCNP weight window generator. Thus, such comparisons were not repeated in this work.

RESULTS

The computational speedups achieved for optimization of individual detector responses are dependent on which detector (near or far) was chosen. They are summarized in Tables I and II for the neutron and gamma tools, respectively. Speedups of ~150/450 and ~6800/72000 for the near/far detectors for the neutron and gamma tools, respectively, were achieved.

Also shown in Tables I and II are the FW-CADIS results, which demonstrate that significant speedups for both near and far detectors can be achieved simultaneously. The effectiveness of the FW-CADIS method, as compared to analog, is also readily apparent by comparing contour plots of the flux and relative uncertainty from each approach. As illustrated in Figures 1 and 2 (for the gamma tool), the analog calculation spends a great deal of time tracking particles deep into the rock formation, where they have little chance of contributing to either detector. The near detector tally converges quite slowly, and the far detector even slower than the near.

In contrast, the FW-CADIS method uses a biased source and an importance map optimized to simulate more particles in the spatial areas and energy groups that contribute more to the detectors at the expense of other portions of phase space—converging the tallies more efficiently. This is shown in Figures 3 and 4 for the gamma tool, where it is readily apparent that the forward adjoint source weighting is effective for balancing the number of simulated particles in each detector so that the two tallies converge at nearly the same rate.

CONCLUSIONS

The CADIS and FW-CADIS methods are both very effective for improving the computational efficiency of nuclear well-logging simulations. Comparisons of individual detector optimizations via the CADIS method, which requires separate deterministic and Monte Carlo calculations for each detector, with simultaneous optimization via the FW-CADIS method, which requires two deterministic calculations and a single Monte Carlo calculation, indicate that both approaches yield similar overall computational efficiency. Because both methods are automated within MAVRIC, the user requirements associated with the application of each method are small and comparable. However, because the FW-CADIS method simultaneously optimizes both detectors in a single MAVRIC calculation, whereas individual optimization of detectors with CADIS requires a separate MAVRIC calculation for each detector, application of the FW-CADIS approach is easier and more straightforward for the user. Although individual optimization with CADIS outperformed the simultaneous optimization with FW-CADIS for these problems in terms of total computational time required, the relative efficiency of the FW-CADIS approach is expected to increase as the number of detectors increases because it does not require a separate calculation for each detector.

ACKNOWLEDGMENTS

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REFERENCES

1. T.M. EVANS, T.A. WAREING, “The Solution of Well Logging Problems Using Hybrid Transport Methods on Unstructured Meshes,” *Proc. Mathematics and Computation, Reactor Physics and Environmental Analysis in Nuclear Applications*, Madrid, Spain, September 27–30, 1999, p. 1393.
2. R.P. GARDNER and L. LIU, “Monte Carlo Simulation of Neutron Porosity Oil Well Logging Tools: Combining the Geometry-Independent Fine-Mesh Importance Map and One-Dimensional Diffusion Model Approaches,” *Nucl. Sci. Eng.*, **133**, 80 (1999).
3. K.A. VAN RIPER, T.J. URBATSCH, P.D. SORAN, D.K. PARSONS, J.E. MOREL, G.W. MCKINNEY, S.R. LEE, L.A. CROTZER, F.W. BRINKLEY, J.W. ANDERSON, R.E. ALCOUFFE, “AVATAR—Automatic Variance Reduction in Monte Carlo Calculations,” *Proc. Joint. Int. Conf. on Mathematical Methods and Supercomputing in Nuclear Applications*, **1**, Saratoga Springs, New York, October 6–10, 1997, p. 661.
4. J.C. WAGNER, “An Automated Deterministic Variance Reduction Generator for Monte Carlo Shielding Applications,” *Proc. American Nuclear Society 12th Biennial RPSD Topical Meeting, Santa Fe, NM, April 14–18, 2002*.
5. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, ORNL/TM-2005/39, Version 5, Vols. I-III (April 2005), available from Radiation

Safety Information Computational Center at Oak Ridge National Laboratory as CCC-725.
6. X-5 Monte Carlo Team, *MCNP—A General Monte Carlo N-Particle Transport Code, Version 5. Volume I: Overview and Theory*, LA-UR-03-1987, Los Alamos National Laboratory, Los Alamos, New Mexico (2003).
7. J.C. WAGNER, A. HAGHIGHAT, "Automated Variance Reduction of Monte Carlo Shielding Calculations Using the Discrete Ordinates Adjoint Function," *Nucl. Sci. Eng.*, **128**, 186 (1998).
8. J.C. WAGNER, E.D. BLAKEMAN, and D.E. PEPLOW, "Forward-Weighted CADIS Method for Global Variance Reduction," *Trans. Am. Nucl. Soc.*, **97**, 630 (2007).
9. D.E. PEPLOW, S.M. BOWMAN, J.E. HORWEDEL, J.C. WAGNER, "Monaco/ MAVRIC: Computational Resources for Radiation Protection and Shielding in SCALE," *Trans. Am. Nucl. Soc.*, **95**, 669–671 (2006).
10. R.P. GARDNER, K. VERGHESE, "Monte Carlo Nuclear Well Logging Benchmark Problems with Preliminary Intercomparison Results," *Nucl. Geophysics*, **5(4)**, 429 (1991).

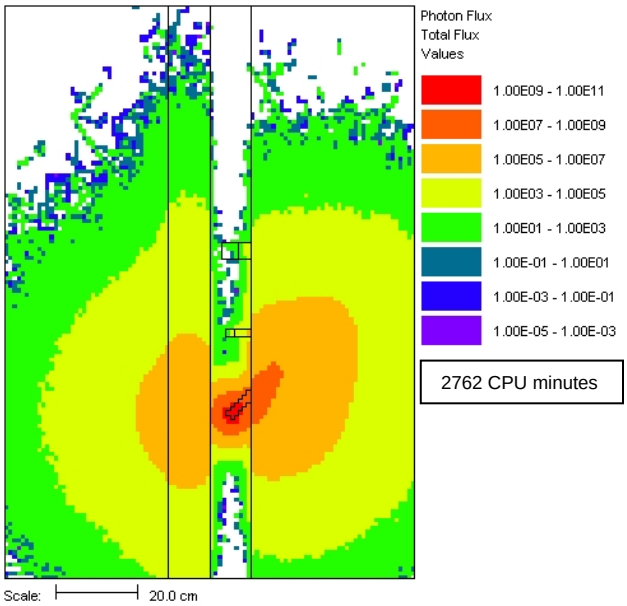

Fig. 1. Analog gamma flux near the well-logging tool.

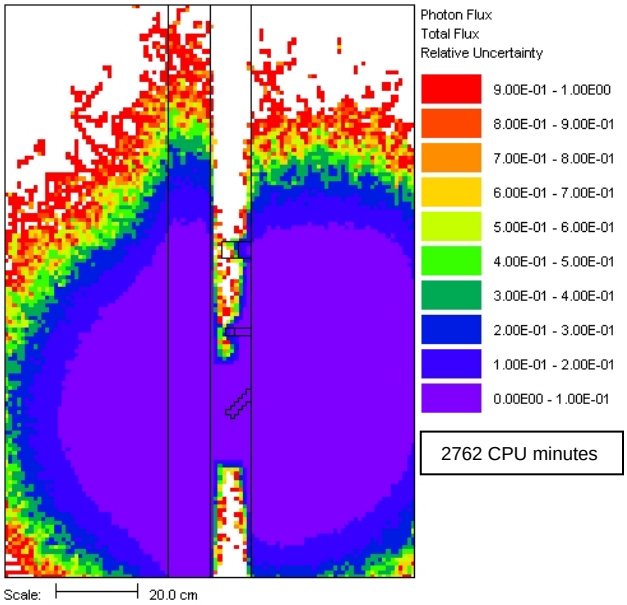

Fig. 2. Relative uncertainty in the analog gamma flux.

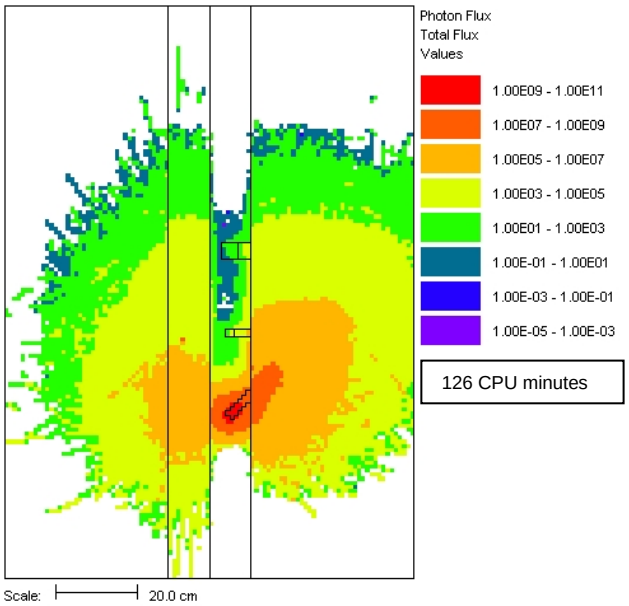

Fig. 3. FW-CADIS flux near the well-logging tool.

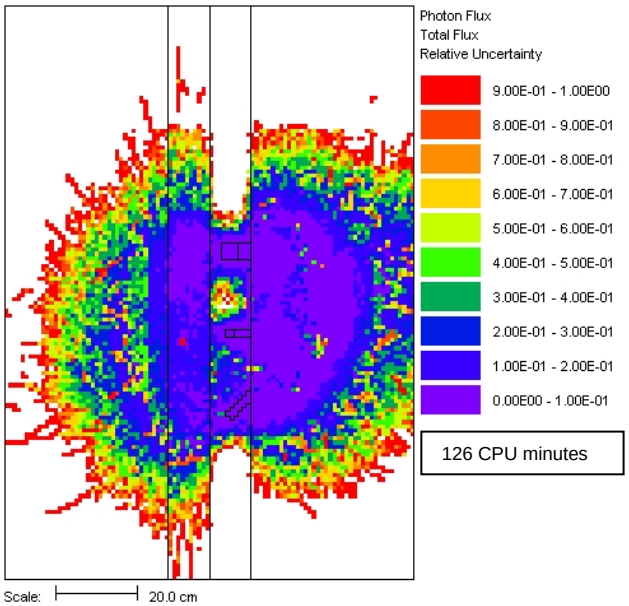

Fig. 4. Relative uncertainty in the FW-CADIS flux.

TABLE I: Summary of results for the neutron tool problem

	Analog	CADIS		FW-CADIS
		Near	Far	
Simulation times (min)				
Forward dis. ord.				8
Adjoint dis. ord.		9	9	9
Monte Carlo	904	125	123	122
Near detector				
Charged pairs/sec	8.820E+08	8.814E+08		8.837E+08
Relative uncertainty	0.78%	0.17%		0.18%
Far detector				
Charged pairs/sec	1.793E+08		1.832E+08	1.833E+08
Relative uncertainty	2.13%		0.27%	0.65%
Monte Carlo FOM[a] ratio				
Near detector	1	154		132
Far detector	1		457	78
Time (min) required for 1%				
Near detector	545	13		21
Far detector	4088		18	69
Time (min) required				
For both detectors	4088	31		69
Time improvement				
Speed-up over analog	1	130		59

TABLE II: Summary of results for the gamma tool problem

	Analog	CADIS		FW-CADIS
		Near	Far	
Simulation times (min)				
Forward dis. ord.				6
Adjoint dis. ord.		7	7	7
Monte Carlo	2762	126	123	126
Near detector				
Charged pairs/sec	1.494E+03	1.545E+03		1.543E+03
Relative uncertainty	8.15%	0.46%		0.61%
Far detector				
Charged pairs/sec	6.130E+01		5.587E+01	5.564E+01
Relative uncertainty	19.14%		0.34%	0.43%
Monte Carlo FOM[a] ratio				
Near detector	1	6830		3867
Far detector	1		71821	43278
Time (min) required for 1%				
Near detector	183547	34		60
Far detector	1012136		21	36
Time (min) required				
For both detectors	1012136	55		60
Time improvement				
Speed-up over analog	1	18321		16748

[a]FOM = Figure of Merit = $1/[(RE)^2T]$, where RE is the relative error and T is computer time.