M&C 2001 Salt Lake City, Utah, USA, September 2001.

THE TIME DEPENDENT MONTE CARLO MIDWAY METHOD FOR APPLICATION TO BOREHOLE LOGGING

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Keywords: Monte Carlo, borehole logging, midway, adjoint, variance reduction

ABSTRACT

The Midway Monte Carlo method aims at increasing the efficiency (Figure Of Merit) of a Monte Carlo calculation using both forward and adjoint simulations to detector response estimation. The theorem that gives the basis for this variance reduction technique states that the detector response can be estimated by a surface integral of the product of the radiation current and the adjoint function on a boundary of a domain containing either the source or the detector. The theorem was extended to time dependent responses and applied to a model of a pulsed neutron-gamma borehole logging tool. The efficiency increased by a factor of 7 to 40 or more in comparison to the value at a standard forward game without putting limits on additional applications of conventional variance reduction techniques.

1. INTRODUCTION

Nuclear tools are frequently used in borehole logging for determining the producible mineral content and other physical properties of possible mineral reservoirs. Combination of measurements based on different physical phenomena can provide a useful data set with high qualitative and quantitative information content. The qualitative information can be extracted from the measured data with the help of accurate numerical simulations or with measurements on well defined experimental setups. There is no doubt that a computer simulation is more plausible for application on any kind of borehole logging environment than calibration and test pit measurements. However, the latter has more in common with physical reality and should be applied as long as computer simulations are not satisfactory. In the case of nuclear borehole logging -due to the three dimensional and generally non-symmetric structure of borehole environment- the only technique applicable is a Monte Carlo simulation where accuracy costs a reasonable amount of computer time.

The unique role that a nuclear borehole logging tool plays at the exploration for undetected reservoirs in previously examined sites, implies a great need for an easy-to-use variance reduction technique that can still be efficient when the detector and the source are both small in comparison to the optical thickness of the setup. The Midway Monte Carlo method (Serov, 1999), developed for time-independent simulations at the Interfaculty

Reactor Institute of the Delft University of Technology is a general variance reduction technique that gives a relatively high efficiency gain when conventional variance reduction techniques fail or require great effort for optimization. The application of the Midway method does not need expertise in the field of variance reduction techniques. Moreover, it does not exclude the additional use of conventional variance reduction techniques.

The Midway Monte Carlo method estimates a current and an adjoint function on a surface that spatially separates the source and the detector with a forward and an adjoint Monte Carlo run, respectively, and integrates their product over all variables of the phase-space to obtain an unbiased estimate for the detector response. For this reason a general Monte Carlo code should be extended to handle the integration over an arbitrary surface. Up till now, the method was implemented into the general Monte Carlo transport code MCNP4C (Briesmeister, 2000) keeping unchanged the main structure of the code and all features, only making available the choice for a Midway treatment.

The theorem on which this method is based, will be derived in the next chapter with special attention to the extension to time dependent problems. The time dependent Midway Method will then be applied to a simplified model of a borehole logging tool with a time dependent (pulsed) neutron source and a photon detector.

2. THEORY OF TIME DEPENDENT MIDWAY MONTE CARLO

2.1. Time-dependent Midway Monte Carlo

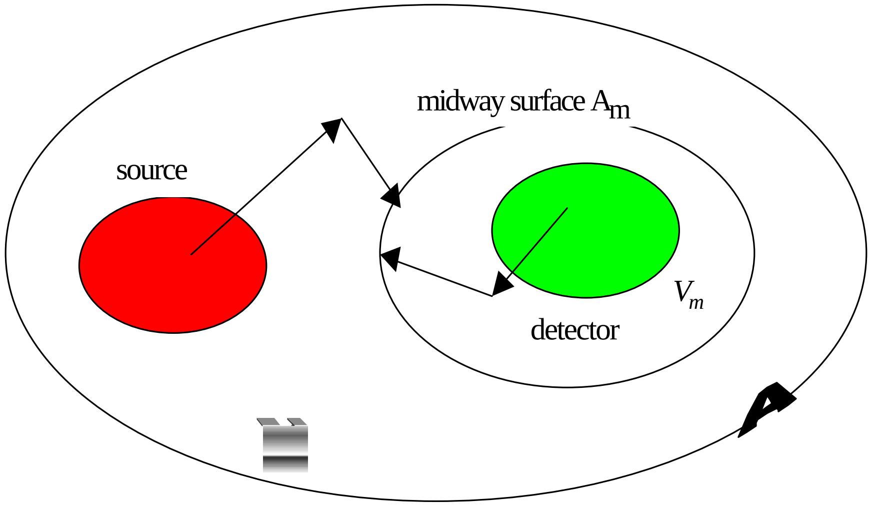
The Midway Monte Carlo method is based upon the application of both a forward and an adjoint calculation to estimate the detector response. Combining a forward and an adjoint calculation results in a more efficient game to estimate a detector response than would be obtained by a single forward or a single adjoint one. For time independent cases the method has been developed and validated for several test cases (Serov, 1999). The extension for time dependent problems will be shown in this chapter.

To derive the theorem that provides the basis for the time dependent Midway method we consider the neutron or photon transport in a (finite or infinite) volume V with a source S and a detector D which are spatially separated (see Fig. 1), and a domain V_m that fully encompasses the detector but totally excludes the source.

The adjoint function $y^*(P, t) = y^*(\boldsymbol{r}, E, W, t)$ and the flux $y(P,t) = y(\boldsymbol{r}, E, W, t)$ are functions of space coordinate $\boldsymbol{r}$, energy E, direction W and time t, where P stands for all variables in the phase-space excluding the time. The flux and the adjoint function are determined by the Boltzmann transport equations, which read in operator form:

$$\frac{1}{v}\frac{\partial y}{\partial t} + W \cdot \nabla y + \mathbf{B}\, y = S \qquad (1)$$

Fig. 1 Midway Monte Carlo calculation.



$$-\frac{1}{v}\frac{\partial y^*}{\partial t} - W \cdot \nabla y^* + \mathbf{B}^* y^* = D \qquad (2)$$

where $\boldsymbol{B}$ and $\boldsymbol{B}^*$ are the forward and adjoint Boltzmann-operators without the streaming term, $S=S(P,t)$ is the particle source and $D=D(P, t)$ is the detector function. Let us consider an initial time moment t_i before the source is turned on ($y(P, t_i)= 0$) and a final moment t_f after the meter reading ($y^*(P, t_f)= 0$). The detector reading integrated over time is:

$$R = \int_{t_i}^{t_f} \int_V D(P,t) y(P,t) dPdt \qquad (3)$$

If we multiply the adjoint equation (2) with y and subtract it from the forward equation (1) multiplied by y^* and integrate the result over the volume V_m, over all directions and the energy domain and between the time events t_i and t_f we obtain:

$$\int_{V_m} \int_{t_i}^{t_f} \frac{1}{v}\left(\frac{\partial y y^*}{\partial t}\right) dt dP + \int_{t_i}^{t_f} \int_{V_m} \nabla \Omega y y^* dPdt = -\int_{t_i}^{t_f} \int_{V_m} Dy \, dPdt \qquad (4)$$

We can evaluate the time integral in the first expression, and apply the Gauss-theorem to the second one:

$$\int_{V_m} \frac{1}{v}\left[y(P,t_f) y^*(P,t_f) - y(P,t_i) y^*(P,t_i)\right] + \int_{t_i}^{t_f} \int_{A_m} \underline{n}\Omega y y^* dPdt = -\int_{t_i}^{t_f} \int_{V_m} Dy \, dPdt \qquad (5)$$

The first term on the left hand side vanishes as $y(P, t_i)= 0$ and $y^*(P, t_f)= 0$, and the right hand side is the detector response itself. So we can write for the Midway response form:

$$R = \int_{t_i}^{t_f} \int_V D(P,t) y(P,t) dPdt = -\int_{t_i}^{t_f} \int_{A_m} \underline{n}\Omega y(P,t) y^*(P,t) dPdt \qquad (6)$$

If we want to know the detector reading at a specific time moment t_m we chose the detector function to be $D(P,t)=D'(P)d(t-t_m)$:

$$R(t_m)=\int_{V_m} D'(P)y(P,t_m)dP=-\int_{t_i}^{t_f}\int_{A_m}\underline{n}\Omega y(P,t)y^*(P,t)dPdt \qquad (7)$$

with the adjoint function $y^*(P, t)$ depending on t_m (see Fig. 2).

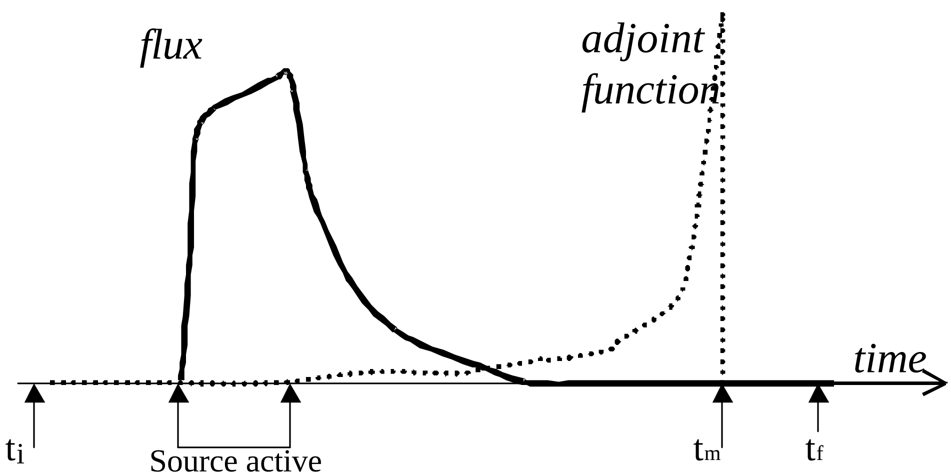


Fig. 2 Schematic time dependence of flux and adjoint function

2.2. Time Dependent Midway Response in a Coupled Neutron-Photon Problem

In the case of a coupled neutron-photon problem, when photons generated at neutron interactions are to be detected, the theory requires further extension to include photon transport. We restrict our derivation to the case of prompt-gamma reactions assuming that a photon is emitted at a reaction without reasonable time delay, i.e. we exclude delayed photons from neutron activation. With subscripts *n* and *p* we denote the neutron and photon quantities, respectively, and use the general Boltzmann equations (1) and (2) with subscript *n* for the neutron transport. The Boltzmann equations for the photon transport read:

$$\frac{1}{v_p}\frac{\partial y_p}{\partial t}+W\cdot\nabla y_p+\mathbf{B}_p y_p=S_p \qquad (8)$$

$$-\frac{1}{v_p}\frac{\partial y_p^*}{\partial t}-W\cdot\nabla y_p^*+\mathbf{B}_p^* y_p^*=D_p \qquad (9)$$

with the adjoint photon source term D_n to be determined and S_p the production term of photons from neutron interactions:

$$S_p(r,E,\Omega,t)=\int\int\Sigma_{pr}(r,E'\rightarrow E,\Omega'\rightarrow\Omega)y_n(r,E',\Omega',t)dE'd\Omega' \qquad (10)$$

The photon detector response is given by:

$$R_p = \int_{t_i}^{t_f}\int_{V} D_p(P.t) y_p(P,t) dPdt \tag{11}$$

To arrive at an alternative expression for R_p we subtract the forward neutron equation (1) multiplied by y^*_n from the adjoint equation (2) multiplied by y_n, and integrating over energy, direction variables and the Midway domain and over time between t_i and t_f:

$$\int_{t_i}^{t_f}\int_{A_m} \underline{n}\Omega y_n y_n^* dPdt = \int_{t_i}^{t_f}\int_{V_m} S_n y_n^* dPdt - \int_{t_i}^{t_f}\int_{V_m} D_n y_n dPdt \tag{12}$$

Repeating the same procedure for the photon equations leads to:

$$\int_{t_i}^{t_f}\int_{A_m} \underline{n}\mathrm{W}\, y_p y_p^* dPdt = \int_{t_i}^{t_f}\int_{V_m} S_p y_p^* dPdt - \int_{t_i}^{t_f}\int_{V_m} D_p y_p dPdt \tag{13}$$

Now we define D_n such that

$$\int_{t_i}^{t_f}\int_{V_m} D_n y_n dPdt = \int_{t_i}^{t_f}\int_{V_m} S_p y_p^* dPdt \tag{14}$$

i.e.

$$D_n\left(r,E,\Omega,t\right) = \int\int \Sigma_{pr}\left(r,E \to E',\Omega \to \Omega'\right) y_p^*\left(r,E',\Omega',t\right) dEd\Omega \tag{15}$$

If we add Eq.(12) to Eq.(13) and recall that the neutron source $S_n = 0$ in the detector region, we can write the Midway response form:

$$R_p = -\int_{t_i}^{t_f}\int_{A_m} \underline{n}\Omega y_n y_n^* dPdt - \int_{t_i}^{t_f}\int_{A_m} \underline{n}\Omega y_p y_p^* dPdt \tag{16}$$

This means that in a coupled neutron-photon problem both the neutron and the photon scores should be tallied and integrated at the same surface to get an estimate for the detector response.

2.3. The Monte Carlo utilization of time dependent Midway response

Utilization of the Midway response requires bilinear integration, which obviously is a problem for any linear Monte Carlo method. To circumvent this problem we apply two separate (forward and adjoint) calculations that are coupled on the Midway surface

A_m. To estimate this integral the scoring domain is subdivided into a number of energy, position, direction and time meshes, to approximate the Midway response form with a finite summation. First we obtain a Monte Carlo estimate for the quantity $\boldsymbol{n}.Wy(P,t)$ = $J(P,t)$ in the forward run, then for $y^*(P,t)$ in the adjoint run with a surface crossing flux estimator for every mesh of the phase-space.

For these calculations the necessary modifications were implemented in the Monte Carlo code MCNP4C. In the MCNP4C realization of adjoint calculation the time sampling is not reversed and flows in the same direction as in the forward calculation. Thus the Midway time dependent response estimate with MCNP will take the form of a convolution in the time variables:

$$R_p\left(t_m\right) \approx R_m = \sum_i^m \sum_j J_{i,j} y^*_{m-i,j} \Delta P_j \Delta t_i \tag{17}$$

Presently the time convolution of the Midway scores is not included in the special Midway version of MCNP4C, but carried out by a separate program using the forward and adjoint scores. However this implementation is neither practically nor theoretically impossible. The error of the Monte Carlo calculation can be estimated for individual scores (Lux and Koblinger, 1991):

$$r^2[J_i] = \frac{\sum_{n=1}^{N_f} (w_n^{(i)})^2}{(\sum_{n=1}^{N_f} w_n^{(i)})^2} - \frac{1}{N_f} \tag{18}$$

where $w_n^{(i)}$ is the statistical weight of a scoring particle. To estimate the error in the Midway response we should sum up the errors of all meshes according to the laws of error propagation:

$$r[R_m] = \frac{1}{R_m} \sqrt{\sum_i^m \sum_j \{r^2[J_{i,j}] + r^2[y^*_{m-i,j}]\}\{J_{i.j} y^*_{m-i,j} \Delta P_j \Delta t_i\}^2} \tag{19}$$

3. APPLICATION OF THE METHOD TO A BOREHOLE LOGGING TOOL

For time independent cases applicability of the Midway method has already been tested for borehole logging (Serov, 1998; Hoogenboom, 1998). The time dependent Midway method is now applied to a simplified model of a Neutron-Gamma borehole logging tool. The tool itself is being used mostly for oil detection in a formation via the estimation of the Carbon/Oxygen ratio, i.e. the ratio of photons originating from an inelastic neutron collision on Carbon over that on Oxygen. The special importance that is given to C/O logging at undetected reservoirs in previously examined sites is due to the fact that a number of conventional tools (e.g. resistivity, electromagnetic) can not be applied after the iron casing is put into the borehole.

The neutron gamma tool has a 14 MeV neutron source emitting neutrons for 100 μs, the detector is a NaI scintillation counter registering the photons after each 25 μs. The emitted neutrons induce photons at inelastic scattering and neutron capture which are detected at relevant energy windows. The tool consists of two NaI detectors separated with Tungsten shielding from the source.

In our simplified model (see Fig. 3) the tool is centered in the middle of a cylindrical borehole with steel casing surrounded by a SiO_2 formation with porosity of 23%. The borehole is filled with salty water. The optical thickness of the formation is much larger than the sizes of the detector and the source. Therefore a conventional forward calculation can be rather inefficient and in this geometry with a small detector an adjoint run would neither help. For conventional variance reduction techniques their optimization needs several iteration steps and reasonable expertise.

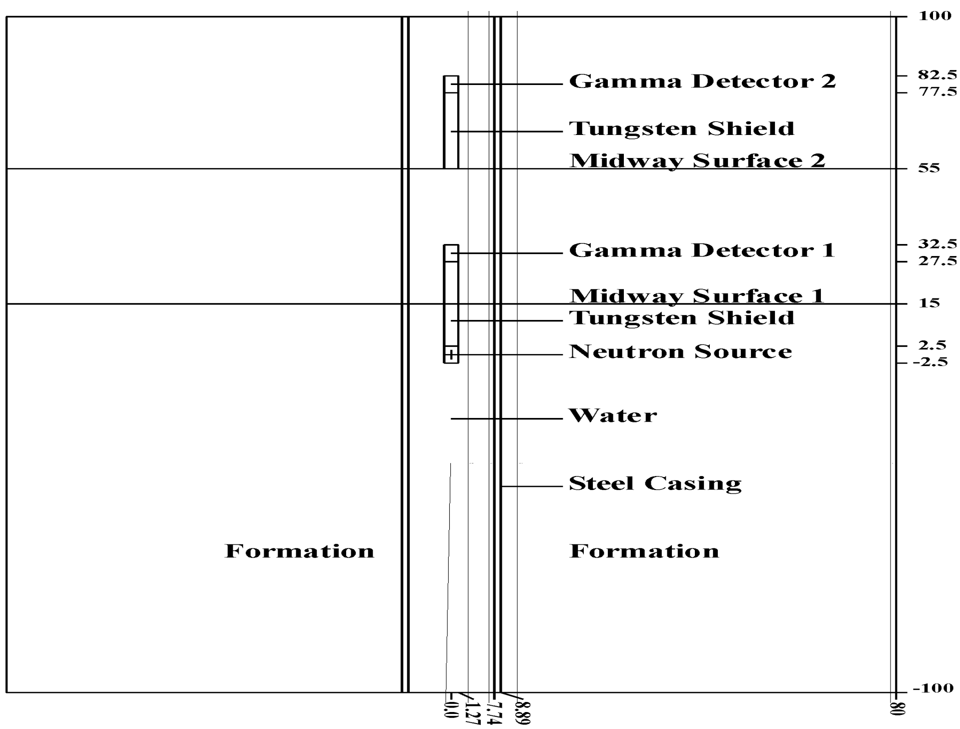


Fig. 3 Model geometry (dimensions in cm)

The Midway response estimation needs the discrete representation of flux and adjoint function. The adjoint Monte Carlo simulations usually apply multigroup energy treatment for adjoint calculations to overcome difficulties an adjoint calculation rises. For the calculations the standard MCNP ENDF-VI multigroup libraries were used allowing 30 neutron and 12 photon energy groups. 11 angular and 10 polar meshes were defined for the solid angle requiring the utilization of the so-called user bins in MCNP. The Midway surface was segmented into 155 parts with overlapping cylinders and for time we applied 20 meshes with width of 25 μs up to 500 μs. For the Midway surface a plain was applied between the source and the detector (see Fig. 3). For the adjoint calculation the black absorber variant (Serov, 1999) was used allowing to simulate adjoint particles only up to the Midway plain.

The discrete representation of the phase-space variables poses the only limitation for applying the Midway method to this borehole logging problem. The allocated memory for all meshes as double precision words can easily exceed the available physical memory of conventional workstations. Therefore the memory allocation structure of MCNP4C was modified to be able to handle more segments of the phase-space. As the number of applicable meshes is not infinite, for an optimal setup of the Midway calculation one should adjust the mesh boundaries to obtain sufficiently detailed information about the flux and the adjoint function.

For comparison of the results in accuracy and calculation efficiency we ran a conventional forward simulation with the same multigroup cross section library and with the same time intervals. The efficiency is qualified by the Figure Of Merit that reads:

$$FOM = \frac{1}{r^2 T} \tag{20}$$

where T is the computer time measured in minutes and r is the relative error of the Monte Carlo calculation. The reference forward run and the Midway run were performed on the same Compaq Alpha 670 MHz workstation.

3.1 Midway and regular forward Monte Carlo calculations for the near detector

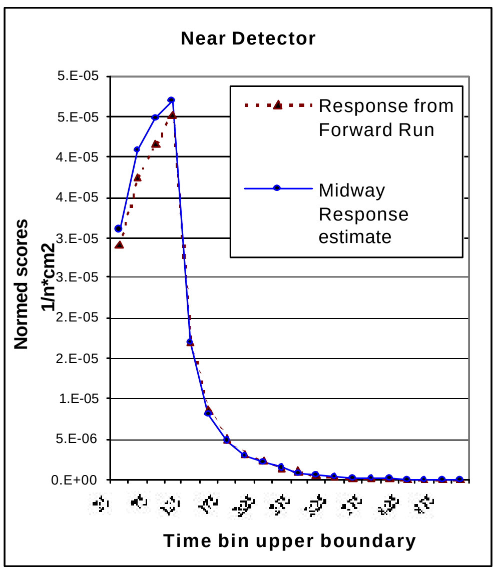
For the “near“ detector (*Gamma Detector 1*) the Midway plane was placed an equal distance from both the detector and the source. In the Midway forward and adjoint run the number of histories were $2*10^6$ for each calculation. The results of the regular forward and the Midway response estimate are shown for the near detector in Table 1.

The efficiency gain was quantified by the ratio of the Figures of Merit for each time mesh in both cases. This measure can be seen in Fig. 4 for those time intervals where the statistics of the regular forward run was reliable i.e. the relative variance for the scores remained below 10%. From the results of Table 1 we can conclude that the efficiency gain of the Midway method over a regular Monte Carlo calculation for this borehole logging problem shows a strong time-dependence and is in the range of a factor of 7 to 20 and is likely to be much more for the small values of the detector response at large times, where the error in the forward calculation was not reliable in our calculation. For a time independent case the efficiency increase is a factor of 8.

Table 1. Numerical results for the near detector

Upper Time Bounds (*ms*)	Regular Forward Run			Midway Response Estimate			Efficiency Ratio
	Response *$1/n*cm^2$*	Relative Error *(%)*	FOM	Response *($1/n*cm^2$)*	Relative Error *(%)*	FOM	
25	$2.91*10^{-5}$	1.80	25.49	$3.10*10^{-5}$	0.70	185.7	7.3
50	$3.75*10^{-5}$	1.58	33.08	$4.08*10^{-5}$	0.58	271.9	8.2
75	$4.15*10^{-5}$	1.47	38.22	$4.47*10^{-5}$	0.53	320.0	8.4

100	$4.51*10^{-5}$	1.43	40.38	$4.68*10^{-5}$	0.51	345.5	8.6
125	$1.69*10^{-5}$	1.98	21.06	$1.68*10^{-5}$	0.51	350.4	16.6
150	$8.59*10^{-6}$	2.63	11.94	$8.14*10^{-6}$	0.64	224.8	18.8
175	$4.96*10^{-6}$	3.24	7.87	$4.70*10^{-6}$	0.77	152.5	19.4
200	$3.11*10^{-6}$	3.98	5.21	$3.01*10^{-6}$	0.90	113.0	21.7
225	$2.33*10^{-6}$	4.59	3.92	$2.00*10^{-6}$	1.06	81.4	20.8
250	$1.38*10^{-6}$	5.68	2.56	$1.41*10^{-6}$	1.34	50.5	19.7
275	$1.02*10^{-6}$	6.52	1.94	$9.33*10^{-7}$	1.61	35.0	18.0
300	$6.55*10^{-7}$	7.71	1.39	$6.60*10^{-7}$	1.99	22.9	16.5
325	$4.68*10^{-7}$	9.12	0.99	$4.60*10^{-7}$	2.44	15.2	15.3
350	$2.89*10^{-7}$	12.43	0.53	$2.95*10^{-7}$	2.32	16.9	31.7
375	$1.64*10^{-7}$	14.54	0.39	$2.01*10^{-7}$	2.88	11.0	28.1
400	$1.74*10^{-7}$	15.7	0.34	$1.39*10^{-7}$	3.59	7.1	21.1
425	$9.95*10^{-8}$	20.59	0.19	$1.00*10^{-7}$	4.38	4.7	24.3
450	$7.49*10^{-8}$	22.61	0.16	$6.64*10^{-8}$	5.16	3.4	21.1
475	$5.66*10^{-8}$	29.05	0.10	$4.56*10^{-8}$	4.38	4.7	48.3
500	$3.57*10^{-8}$	52.07	0.03	$3.52*10^{-8}$	7.17	1.8	58.0
Total	$1.93*10^{-4}$	0.67	182	$2.02*10^{-4}$	0.24	1599	8.78
Number of histories	10^7			$4*10^6$			
CPU time	121 *min*			111 *min*			



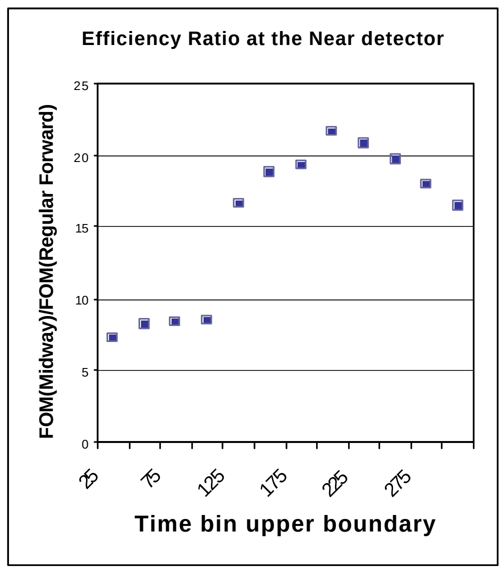


Fig. 4 Comparison of responses and efficiency for the near detector

Further efficiency gains can be obtained by proper optimization of the positioning of the Midway plane and the choice of the number of adjoint to forward histories. The computer time elapsed during the Midway forward and adjoint runs for an equal number of histories is almost twice as much as in a regular forward run with the original MCNP4C code. This is not an inherent property of the Midway method but probably due to frequent page swapping in the computer because of the very large memory needed by the time-dependent Midway method. It is being investigated how to diminish the swapping.

3.2 Midway and regular forward Monte Carlo calculations for the far detector

The second Midway plane was rather arbitrarily placed closer to the “far” detector (*Gamma detector 2*) and the same number of histories and mesh structure was applied. For the Midway response estimate we used separate runs for the adjoint histories because of the different adjoint sources. In the regular forward run after 350 μs the efficiency is too low to get reasonable number of scores. Moreover, some of the time bins have no scores at all. Comparison of the results and the efficiencies therefore can hardly be quantified. The high relative errors (see Table 2 and Fig. 5) of the regular forward simulation does not allow the acceptance of forward time bin scores and the value of a Figure Of Merit.

Table. 2 Numerical results for the far detector

Upper Time Bounds *(ms)*	Regular Forward Run			Midway Response Estimate			Efficiency Ratio
	Response *$1/n*cm^2$*	Relative Error *(%)*	FOM	Response *($1/n*cm^2$)*	Relative Error *(%)*	FOM	
25	$3.67*10^{-7}$	15.9	0.33	$3.13*10^{-7}$	3.00	9.92	30.2
50	$4.97*10^{-7}$	13.4	0.46	$4.64*10^{-7}$	2.41	15.44	33.6
75	$4.87*10^{-7}$	14.1	0.42	$5.07*10^{-7}$	2.23	18.08	43.4
100	$6.01*10^{-7}$	11.6	0.62	$5.69*10^{-7}$	2.06	21.09	34.1
125	$2.25*10^{-7}$	16.5	0.30	$2.60*10^{-7}$	2.47	14.73	48.5
150	$1.79*10^{-7}$	19.8	0.21	$1.45*10^{-7}$	2.87	10.87	51.3
175	$1.22*10^{-7}$	21.4	0.18	$9.21*10^{-8}$	3.40	7.77	43.0
200	$1.02*10^{-7}$	24.6	0.14	$6.59*10^{-8}$	3.79	6.23	45.6
225	$2.34*10^{-8}$	35.1	0.07	$4.31*10^{-8}$	4.21	5.06	75.4
250	$1.53*10^{-8}$	51.2	0.03	$3.80*10^{-8}$	5.43	3.03	96.1
275	$1.60*10^{-8}$	45.9	0.04	$2.80*10^{-8}$	5.81	2.65	67.7
300	$2.09*10^{-8}$	44.5	0.04	$1.80*10^{-8}$	6.67	2.01	48.3
325	$5.95*10^{-9}$	72.5	0.02	$1.30*10^{-8}$	8.55	1.23	78.0
350	-	-	-	$1.11*10^{-8}$	10.1	0.88	-
375	-	-	-	$6.79*10^{-9}$	11.2	0.72	-
400	-	-	-	$4.64*10^{-9}$	13.4	0.50	-
425	-	-	-	$4.27*10^{-9}$	14.8	0.41	-
450	-	-	-	$5.48*10^{-9}$	19.2	0.24	-
475	-	-	-	$2.87*10^{-9}$	20.5	0.21	-
500	-	-	-	$1.19*10^{-9}$	17.7	0.29	-
Total	$2.73*10^{-6}$	5.4	2.79	$2.59*10^{-6}$	0.92	106	38
Number of histories	10^7			$4*10^6$			
CPU time	121 *min*			111 *min*			

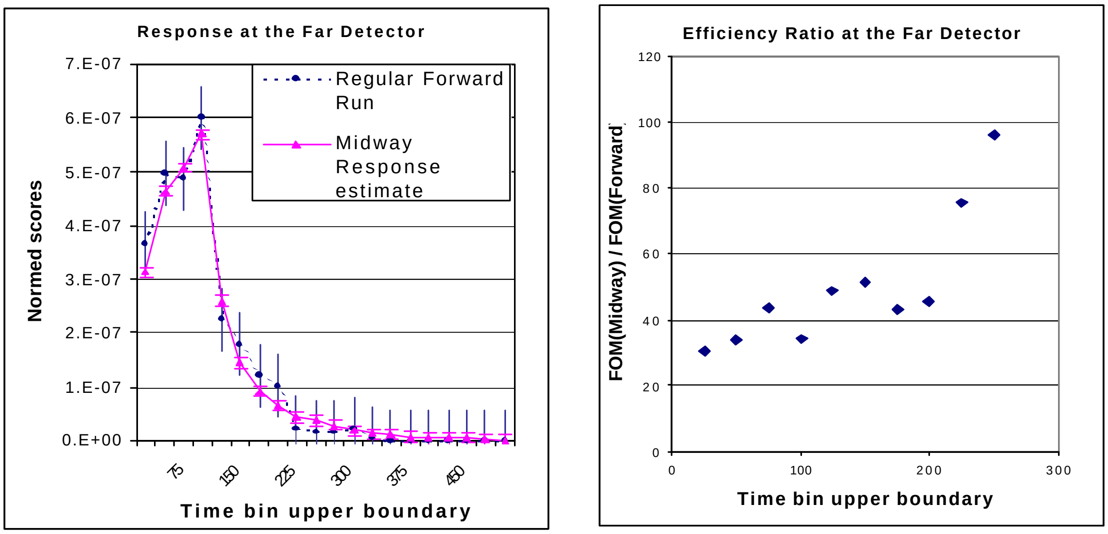


Fig. 5 Comparison of responses and efficiency for the far detector

The time independent response (total detector response) can be a basis of estimating the efficiency gain. Comparing the Midway and the regular forward total response results, we can conclude that the average efficiency gain is a factor of 38.

In both cases the efficiency gain is obtained because in both forward and adjoint calculations the particles need to be transported only from the source or the detector to the Midway surface. Moreover the target area of the Midway surface is in general much larger than the boundary surface of the source or the detector. As the attenuation of the particle intensity is in general roughly exponential with the distance to be covered, splitting up this distance in two about equal parts leads to an attenuation involving the product of two exponentials each over half the space. The advantage of splitting up the distance will strongly increase with the distance between source and detector. This is confirmed by the much higher efficiency gain for the far detector compared to the already considerable efficiency gain for the near detector.

4. DISCUSSION AND CONCLUSION

The time dependent Midway method has proved its applicability for time dependent problems. The method showed a considerable efficiency gain, notwithstanding the fact that the parameters for the Midway time dependent coupling were not optimized at all. The efficiency gain was calculated only for those cases where the efficiency measure (Figure Of Merit) was reliable. The estimated efficiency gain can then exceed for certain time meshes the calculated value.

The applied Midway surface position and phase-space segmentation was not optimized. Therefore further efficiency gain can be expected. Comparison of the response estimates for different time bins for the near detector shows a slight but apparently systematic difference between the Midway estimate and the regular forward calculation for those bins when the neutron source is on. It has to be investigated whether this difference is significant and if so, whether it is caused by the time convolution procedure, the width of the time bins or insufficient segmentation of the Midway surface area.

Normally, variance reduction methods will be applied in a regular Monte Carlo calculation like importance sampling. This is not applied for the above sample calculations to get a realistic comparison. However, further improvement can be achieved with application of conventional variance reduction techniques for both the Midway forward and Midway adjoint runs.

The Midway method is suited for estimating any kind of response in a Monte Carlo calculation of a source-detector system. If we consider the adjoint function or the radiation current at the Midway surface as detector responses we can estimate it also using a second Midway plane between source and the first Midway plane or between the detector and the first Midway plane. This technique can give higher efficiency than the calculation with a single Midway plane (Hoogenboom, 2001).

We conclude that the presented time dependent Midway method is capable of handling time dependency for coupled neutron-photon problems for prompt-gamma reactions, and has a great potential for increasing the calculational efficiency of borehole logging problems.

ACKNOWLEDGMENTS

This work was supported by the European Union under contract NNE5-2000-20166 for the project Improved Radiation Transport Modelling for Borehole Applications.

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