Proceedings of Eurotherm73 on Computational Thermal Radiation in Participating Media
15-17 April 2003, Mons, Belgium

Detecting inhomogeneity in a turbid medium

Siew Kan Wan[1], Zhixiong Guo[1*], Sunil Kumar[2], Janice Aber[3] and Bruce A. Garetz[3]

[1]*Department of Mechanical and Aerospace Engineering*
Rutgers, The State University of New Jersey
98 Brett Road, Piscataway, NJ 08854, USA.
[2]*Department of Mechanical Engineering*
Polytechnic University, 6 Metrotech Center, Brooklyn, NY 11201, USA.
[3]*Department of Chemical Engineering and Chemistry*
Polytechnic University, 6 Metrotech Center, Brooklyn, NY 11201, USA.

*Corresponding author: (732)445-2024, guo@jove.rutgers.edu

Abstract

In this paper, a new method for detecting inhomogeneity in turbid media is proposed and investigated both numerically and experimentally. An ultrafast laser, whose pulse width is in the range of picoseconds or femtoseconds, is used as the detecting source and backscattered light signals are collected around the boundary of the target. This novel technique that we used to locate inhomogeneity is called decaying log slope analysis. Monte Carlo simulation results have shown that a tiny absorbing inhomogeneity in a highly scattering medium can be visualized via the analysis of a V-shaped groove of log slope of the detected temporal intensity profiles. Experiment studies in a rectangular tissue phantom with the inclusion of a graphite of 1.6mm in diameter yield similar results.

1. Introduction

Detecting inhomogeneity in a turbid medium using optical tomography technique as a non-invasive tool is of paramount importance in many practical applications, such as in biomedical imaging and diagnosis, safety inspection on aircrafts and submarines, LIDAR technique, etc. The application of near infrared (NIR) ultrafast laser pulse in optical tomography has been studied intensively by various research groups because it offers a promising method in assessing the optical properties of an absorbing-scattering medium. Unlike x-ray based computed tomography (CT) that relies on high energy particles, optical tomography utilizes low powered NIR laser pulse as an input source. There are several advantages associated with time-resolved optical imaging that is worth pursuing for. For example, the instrumentation system is small, less complex and that the signal detection can be easily obtained with less manipulation and restriction as compared to frequency-resolved counterpart. However, the detection of foreign objects inside a turbid medium proves to be a challenging task in optical tomography because incident laser light will experience energy attenuation and multiple scattering or diffusion process within the turbid medium before being detected by detectors located at boundary surfaces. With the advancement in laser technology, laser pulse in sub-picoseconds and femtoseconds time scale has opened a new and promising opportunity for time-resolved optical imaging. In this technology, either scattered, ballistic or snake component of light signals can be utilized for optical imaging to optically thick medium as long as the detected signal is strong enough to be filtered from background noise and experimental uncertainty. Several recent studies [1-3] have reported on the feasibility of determining optical properties of thick turbid media from time-resolved light scattering measurements via simply applying diffusion theory.

In this paper, we have investigated the possibility of detecting inhomogeneity in turbid media by analyzing the temporal signals of the decaying tail that is a pulse of photons experiencing multiple scattering events. We propose a new log slope analysis method that is simple, innovative and efficient. Its feasibility in detecting inhomogeneity in a turbid medium is verified experimentally by detecting an embedded tiny graphite in a block of tissue phantom. A Monte Carlo simulation program has been developed to model the 3D transient laser radiative transfer for further investigations in relevant analyses. Brewster and Yamada [3] have shown that the asymptotic log slope of a homogeneous semi-infinite slab is steeper as the scattering albedo decreases. A study conducted by Zaccanti et. al. [4] also shows that there is a significant dependence between scattering coefficient of a homogeneous medium and the broadening of laser pulse, thus affecting the steepness of asymptotic log slope. Recently, Guo and Kim [5] further showed that the asymptotic log slopes of reflected signals in a finite 3D geometry are proportional to the absorption coefficient of the embedded inhomogeneity. Our concept of detecting inhomogeneity of relatively high absorption than the surrounding tissue is to evaluate the log slope from reflected laser signals at various positions on the medium's surface. The influences of absorption strength and size of the embedded inhomogeneity on the log slope will be studied. The effectiveness of laser and detector positioning in locating the graphite inclusion is also examined.

2. Theory

The details of the experimental setup will be discussed in the next section. The simulation is performed using a Monte Carlo multidimensional transient radiative transfer program basically adapted by Guo et. al. [6]. The Monte Carlo simulation models photons propagation in homogeneous turbid medium by calculating the movements of a large number of photon bundles. Each emitted photon bundle begins from its initial position and makes its way into the participating medium by a certain path length determined from statistical distribution. It will then experiences scattering, absorption as well as reflection. Scaled isotropic scattering is used to reduce CPU time in calculations although the scattering of tissue phantom is anisotropic. Such an approximation does not introduce obvious errors in the diffusion part of the signal as shown by Guo et. al [7]. Fresnel reflection [8] at the tissue-air boundaries consideration was incorporated because there is a significant refractive index mismatch between them (n_{air}=1, n_{tissue}=1.59). Total internal reflection occurs when the incoming angle is greater and equal to the critical angle while partial specular reflection occurs otherwise. The energy attenuation of each photon bundle is determined using the scattering albedo method.

Additional subroutines are added to simulate light propagation inside a turbid medium with the presence of a graphite inclusion in the present study. The graphite inclusion is treated as a highly absorbing and low reflecting material. As such, large amount of radiative energy will be absorbed when the scattered photon bundles come into contact with the graphite's surface. The exact values of absorption and reflection for graphite are unavailable, but we assumed a 95% absorption and 5% reflection. Actually, the asymptotic log slope changes less than 1% for results with absorption ranging from 90%-100% because only a small fraction of emitted photon bundles interact with the tiny graphite inclusion. Interacting photon bundles will be specularly reflected with a substantial loss of energy content and no photon bundles are allowed to penetrate the graphite inclusion.

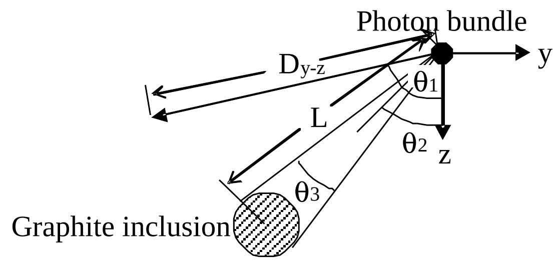

Figure 1. –Schematic of a photon bundle near the region of graphite inclusion

Figure 1 shows a photon bundle located near the graphite inclusion with $D_{y\text{-}z}$ as the projected vector of it next trajectory in y-z plane. The first test to determine whether the photon bundle hits the inclusion is to check if the vector $D_{y\text{-}z}$ lies inside the angle of view, θ_3 when the norm of it is greater than |L|. The angles θ_1, θ_2 and θ_3 can be calculated from

$$\theta_1 = \arctan\left(\frac{D_y}{D_z}\right) \tag{1}$$

$$\theta_2 = \arctan\left(\frac{L_y}{L_z}\right) \tag{2}$$

$$\theta_3 = 2\left[\arcsin\left(\frac{r_{graphite}}{|L|}\right)\right] \tag{3}$$

Thus, the contact happens when $|\theta_1 - \theta_2| < (\theta_3/2)$. The test is incomplete because the photon might fall inside the graphite region even though $D_{y\text{-}z} < |L|$. Thus the second simpler test is to check if the final trajectory is located inside the circumference of the graphite inclusion. Once the photon bundle hits the surface, its energy content is reduced by 95% before being reflected off the graphite's surface for the remaining distance of the current trajectory.

3. Simulation/Experimental Model

3.1 Tissue Phantom

Overall simulation model consists of a rectangular tissue phantom implanted with a tiny graphite cylinder that serves as a source of inhomogeneity. The tissue phantom is made from a mixture of polystyrene matrix and silica microspheres of 1μm (±10%) in diameter with 1.46 refractive index value. Silica microspheres are used as scattering agent and have a concentration by volume of 0.86% of the entire tissue phantom that measures 16.1mm x

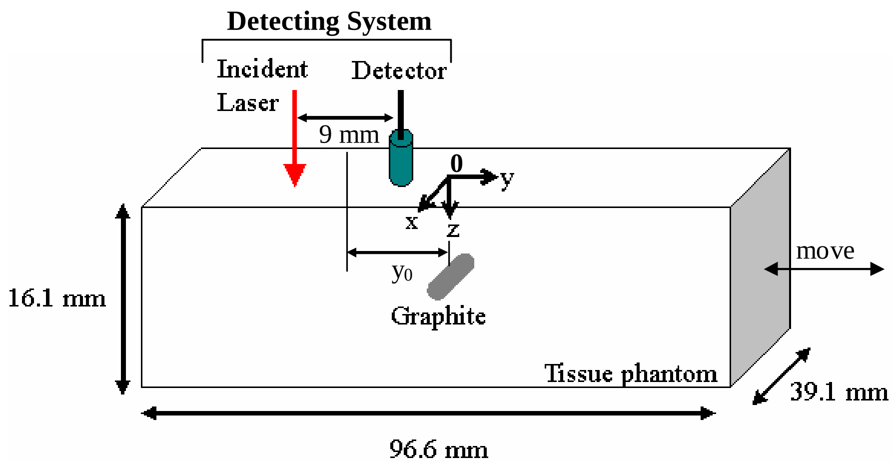

Figure 2. -Sketch of experimental model: The laser and detector head is scanning over a tissue phantom with a graphite inclusion, through horizontally moving the sample.

96.6mm x 39.1mm in height, length and depth. The above preparation of tissue phantom yields a quasi-homogeneous turbid medium with scattering coefficient of $0.37mm^{-1}$ and negligible absorption for visible wavelengths as no artificial absorbing agent is added during the process. The refractive index of this phantom matrix at 532nm wavelength is found to be 1.59. The tissue block is held on a translation stage and is free to move from left to right during scanning process.

A tiny piece of graphite cylinder measuring 1.6mm in diameter and 39.1mm in length is inserted horizontally at the center of the tissue block. Graphite is a highly absorbing material and therefore, most photons that interact with it will be absorbed before they pass through. However, a small percentage of the photons will be reflected back into the tissue phantom for further internal scattering.

3.2 Incident Laser and Detector Condition

The pulse laser source is generated via a Nd^{3+}:YAG mode-locked laser which has a pulse width of 60ps at a repetition rate of 76 MHz. The setup of laser system has been given in Guo et. al. [7]. Laser beam is delivered to the surface of the tissue block via window output. The beam is incident at the top face of the tissue. The beam's diameter is 1.3mm and the temporal Gaussian pulse is describe by the equation below

$$I = I_0 \exp\left[-4 \ln 2 \times \left(\frac{t}{t_p} - 2.0\right)^2 \right] \tag{4}$$

where I_0 is the maximum pulse intensity, and t_p the pulse width. In the present Monte Carlo simulation, a total of 1×10^8 photon bundles are used for an impulsive input where Duhamel's theorem of superposition is applied to incorporate the input pulse profile in a method as described by Guo and Kumar [9].

In the experiment, the detector, which is an optical fiber approximately 100μm in diameter connected to an ultrafast optical oscilloscope, is positioned at a fixed distance of 9mm away from the laser incident location in the positive y-axis direction. The laser beam and optical fiber are collectively known as the detecting system. y_0 refers to the detection position, and it is measured from the origin of Cartesian coordinate to the mid-point between laser and detector. The optical oscilloscope model is OOS-01 made by Hamamatsu and has a photon counting capability with time resolution of 10ps.

4. Results and Discussions

4.1 Choice of Log Slope

In this paper, we have developed a new technique called decaying log slope analysis to detect inhomogeneity in turbid media. *Figure 3* shows the typical detected laser signals in both linear and log scales, where the results of MC simulation are also plotted. There exists a nearly straight decaying tail in the log scale and a log slope can be calculated for each detecting position. The representative results in *Fig. 3* are from the case that the detecting system is positioned at -3mm from the center with a graphite implanted at the rectangular tissue center. The log slope varies with localized absorption coefficient. Regions with higher absorption portray steeper log slope than those with lower absorption coefficient. Therefore, it is possible to detect a localized area with high absorption property inside a turbid medium by performing scans across the surface of the medium.

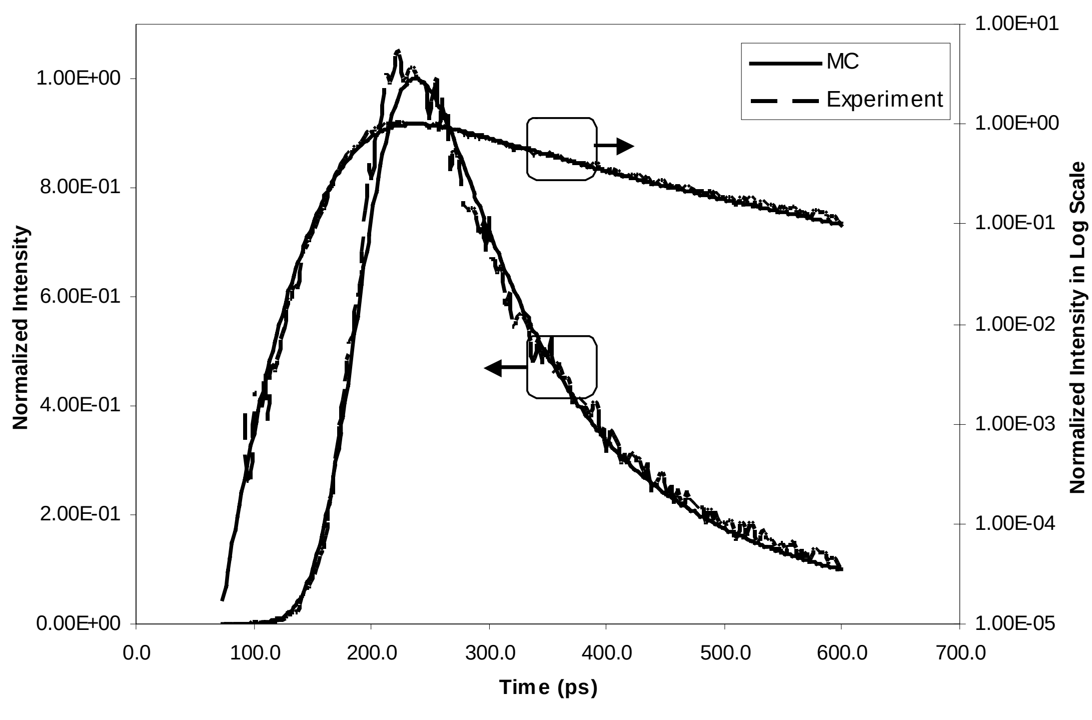

Figure 3. –Experimental and MC simulated laser signals detected at y_0 = -3mm.

Figure 4 shows the representative log slopes, in the interval 400-500ps used in our analysis for signals collected at y_0 = -25mm and y_0 = -3mm, respectively. The log slope is calculated by fitting an exponential function over this interval. At -25mm, the absorption effect from the graphite inclusion is very slight. Therefore, the log slope profile is a result of purely laser diffusion in the homogeneous region. For detection position near the presence of graphite inclusion, such as at y_0 = -3mm, the influence of absorption is great and tends to create steeper log slopes. When the analysis is applied to all signals detected from various positions, the location of the graphite inclusion can be determined.

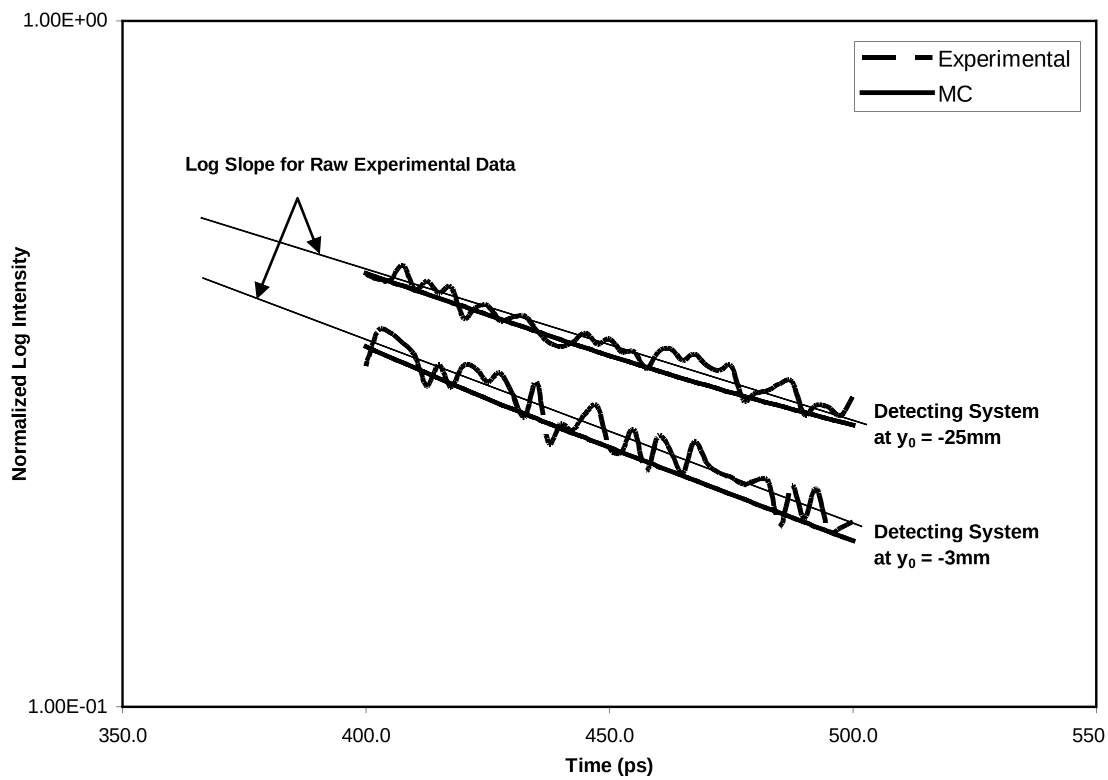

Figure 4. –Log intensity between 400-500ps for signals detected at y_0 = -25mm and -3mm.

4.2 Detection of Inhomogeneity

Laser signals collected at various detection positions in experiment and Monte Carlo simulation are investigated. The Monte Carlo simulation is performed on a PC with a 1.7GHz Pentium 4 processor equipped with 256 MB RAM. The result from each detector position with 1×10^8 incident photon bundles requires approximately 1.4hrs computation time. This value of photons is chosen to reduce computation time without compromising the accuracy. The simulation for each detector position is repeated for a total of 10 times to obtain a statistical error. Experimental procedures have been performed for 3 times for each detector position.

Correct:

symmetry => symmetrical

Figure 5 shows the average log slope values plotted with respect to detecting positions from the center of coordinate system. The raw signals from both experiment and Monte Carlo simulation are normalized before their respective log slopes are calculated. The v-shape log slope profile in *Fig. 5* has demonstrated the feasibility of detecting highly absorbing inhomogeneity in turbid media by utilizing decaying log slope characteristic. The tip of the profile indicates the position of the graphite inclusion, but the profile is not symmetry because of the 9mm gap between laser and detector in the experimental design. However, the exact size of the inhomogeneity (ϕ=1.6mm) is not clearly obtainable in the v-shaped log slope profile. The affecting region in *Fig. 5* is about 10mm. This may be caused by two reasons. The first reason is that the high absorbing inhomogeneity is embedded in a depth of 8.05mm from the surface. Second, there is a 9mm gap between the incident laser beam and the detector. Since we used a window output type laser system, we could not put the detector to a closer distance to the laser incident spot in order to avoid the intervention of reflection from the detector and the collection of directly reflected light from the surface of the incident spot. It is also noted that there is a slight mismatch between the experimental and Monte Carlo results. This mismatch is probably due to the fact that the prepared tissue phantom's optical properties are quasi-homogeneous and not homogeneous as assumed in Monte Carlo simulation, and that the relatively strong noise in experiment associated with the photon counting technique.

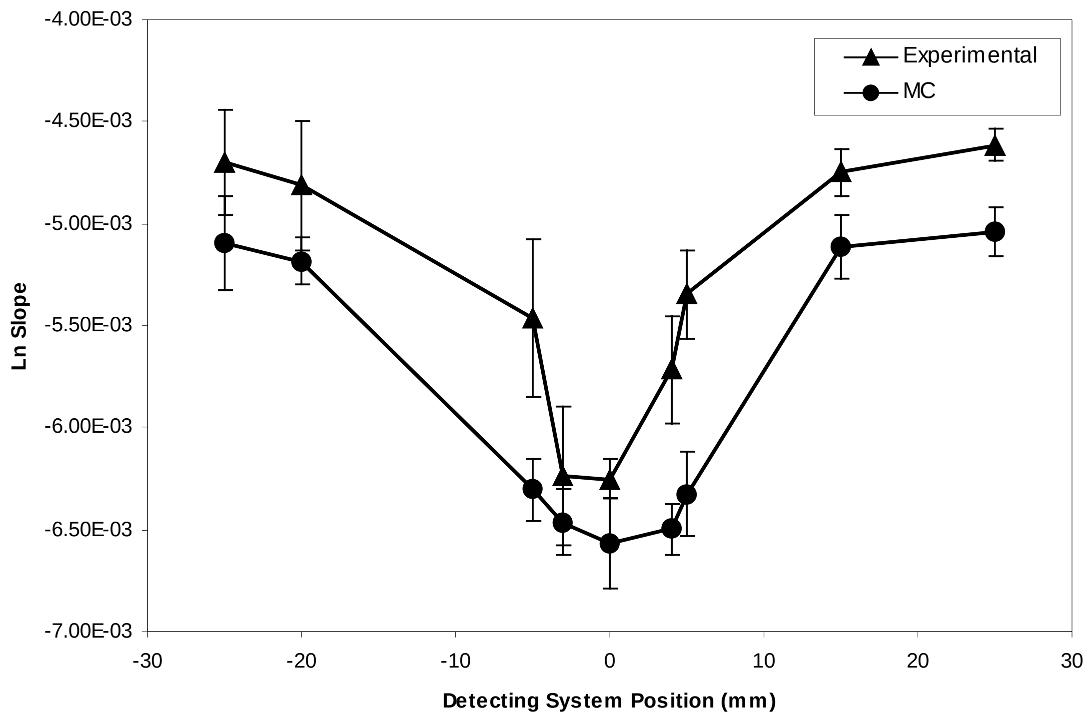

Figure 5. – Experimental and Monte Carlo comparison: average log slope with error bar versus detector position.

4.3 Effect of graphite inclusion diameter

The effect of graphite inclusion diameter in inhomogeneity detection is being investigated numerically. The optical properties of tissue phantom, the position of graphite inclusion and the detecting system remain unchanged. *Figure* 6 shows the average log slope plotted with respect to the position of detecting system for the case where laser and detector are separated by 9mm. The depth of v-shape groove begins to diminish with reduction in graphite diameter as expected because less radiative energy is absorbed. The minimum detectable graphite diameter presuming 3% standard deviation in log slope uncertainty measurement is found to be about 0.1mm. The depth of v-shape groove is strongly related to the diameter of the inclusion. The larger the diameter is, the deeper is the v-shape groove.

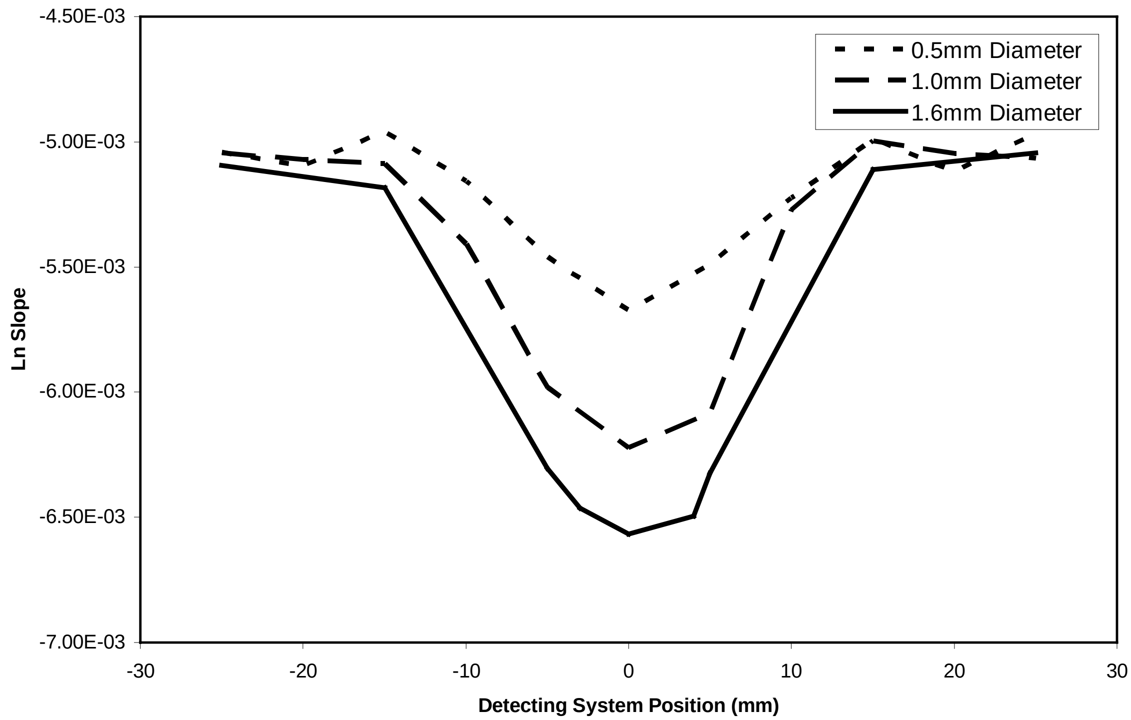

Figure 6. –Effect of graphite's diameter on log slope: laser and detector distance is 9mm

4.4 Effect of depth of graphite inclusion

The effect of depth of graphite inclusion in inhomogeneity detection is being investigated. Unlike the original experimental setup, the Monte Carlo program is modified to simulate the case when the position of laser and detector coincide with each other. Such a modification is try to eliminate the influence of the gap between the laser beam and detector and can easily be achieved experimentally by the use of a fiber optic reflectance probe. *Figure 7* shows the v-shape grooves for graphite embedded at 5.05mm, 8.05mm and 12.05mm below the surface respectively using this new simulation design. The profile is now symmetry along the centerline, i.e. where the graphite inclusion is located. The width of the groove in *Fig. 7* is smaller as compared to previous plots. Apart from that, the overall magnitude of log slope has increased because the detected signal is less diffused and relatively narrower than the 9mm gap laser-detector counterpart. The percentage of graphite inclusion's volume over the entire volume of radiation propagation decreases drastically as the depth of which it is embedded increases. The v-shape deepens when the inclusion is closer to the surface because of increase in absorption. It may be possible to reckon the depth by characterizing the strength of the v-shape.

Correct:

symmetry => symmetrical

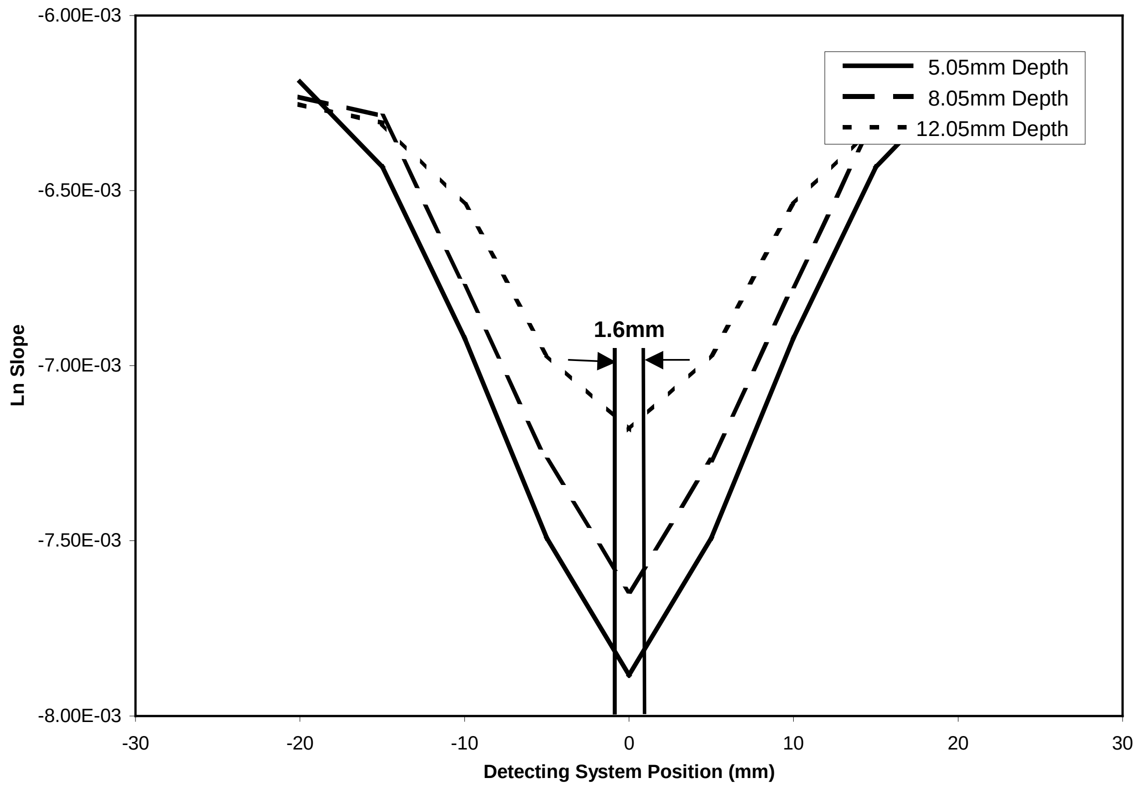

Figure 7. –Effect of graphite inclusion's depth on log slope: laser and detector coincide with graphite diameter 1.6mm.

5. Conclusions

Correct:

base => based

The experimental investigation demonstrated that it is viable to utilize decaying log slope analysis as a quick preliminary technique to detect region with high absorption in a turbid medium. The absorption effect of the graphite inclusion determines the steepness of the log slope and therefore tells us where it is located base on the v-shape profile. Comparison between Monte Carlo and experimental results indicated that it is flexible to model realistic radiation problems. Manipulation in Monte Carlo simulation allowed us to predict new results and investigate the effectiveness of our technique under different circumstances. Overall investigation revealed that it is possible to detect inhomogeneity under much harsher conditions. The rather large distance between laser and detector positions in the current experimental design resulted in asymmetric v-shape profiles and relatively large affecting region. MC simulation has demonstrated that a tiny detecting system (i.e laser beam and detector coincide) could improve the accuracy of detecting inhomogeneity. This new technique could be applied to optically thick medium which may be out of bound for those which rely on transmitted signal as a source of detection. Current study only focuses on locating the position of abnormal inclusion along the scanning positions, but 3-D image reconstruction to further pinpoint the location and size of inhomogeneity is possible and will be our next research focus.

REFERENCES

[1] Ntziachristos, V., Chance, B., (2001) *Accuracy limits in the determination of absolute optical properties using time-resolved NIR spectroscopy*, Med. Phys., Vol. 28 (6)., pp. 1115-1124.

[2] Schmidt, F.E.W., Hebden, J.C., Hillman, E.M.C., Fry, M.E., Schweiger, M., Dehghani, H., Delpy, D.T., Arridge, S.R., (2000) *Multi-slice imaging of a tissue-equivalent phantom by use of time resolved optical tomography*, Applied Opt., Vol. 39, No. 19., pp. 3380-3387.

[3] Brewster, M.Q., Yamada, Y., (1995) *Optical properties thick, turbid media from picosecond time-resolved light scattering measurements*, Int. J. Heat Mass Transfer, Vol. 38, pp. 2569-2581.

[4] Zaccanti , G., Bruscaglioni P., Ismaelli A., Carraresi L., Gurioli M., Wei, Q., (1992) *Transmission of a pulse thin light beam through thick turbid media: experimental results,* J. Opt. Society America. Vol. 31, No. 12, pp 2141-2147.

[5] Guo, Z., and K.H. Kim, (2003) *Ultrafast Laser Radiation Transfer in Heterogeneous Tissues Using Discrete Ordinates Method*, Applied Optics, (in press).

[6] Guo, Z., Kumar, S., San, K.C., (2000) *Multidimensional Monte Carlo simulation of short-pulse laser transport in scattering media*, J. Thermophysics Heat Transfer, Vol. 14, No. 4., pp 504-511.

[7] Guo, Z., Aber, J., Garetz, B., Kumar, S., (2002) *Monte Carlo simulation and experiment of pulsed radiative transfer*, J. Quantitative Spectroscopy & Radiative Transfer, Vol. 73, pp. 159-168.

[8] Bartlett, M.A., Jiang, H., (2001) *Effect of refractive index on the measurement of optical properties in turbid media*, J. Opt. Society America, Vol. 40, No. 10, pp. 1735-1741.

[9] Guo, Z. and Kumar, S., (2002) *Three-dimensional discrete ordinates method in transient radiative transfer*, J. Thermophysics Heat Transfer, Vol. 16, pp. 289-296.