Measuring distance through turbid media: A simple frequency domain approach

A. L. Dayton, N. Choudhury and S. A. Prahl

BME Department, Oregon Health & Science University, United States

ABSTRACT

In both industry and medicine there is no optical technique to measure distance through light scattering media. Such a technique may be useful for localizing embedded structures, or may be a non-contact method of measuring turbid media. The limits of a frequency domain based technique were explored in three polyurethane optical phantoms. We have demonstrated a simple method to measure the distance between an intensity modulated light source and detector in turbid media based on the proportionality of the phase lag to the distance. The limits of the technique were evident for distances less than 5 mm, particularly when $\mu_s' < 0.1\,\mathrm{mm}^{-1}$ and distances greater than 55 mm for the phantoms studied. This method may prove useful in industry and medicine as a non destructive way measure distance through light scattering media.

Keywords: frequency domain, distance

1. INTRODUCTION

In both industry and medicine there is no optical technique to measure distance through light scattering media. Such a technique may be useful for localizing embedded structures, or may be a non-contact method of measuring turbid media.

2. MATERIALS & METHODS

2.1 Experimental System

A system was assembled as shown in Figures 1 & 2. A computer running LabView (National Instruments, v. 2009) was used to control a network analyzer (Hewlett Packard, 8752C) which generated a radio frequency (RF) signal. The RF signal was delivered to a laser diode mount (ThorLabs,TCLDM9) on which an 638 nm laser diode (Sanyo, DL6148-030) was mounted. The laser diode was biased by a direct current from the driver (ThorLabs, LDC 210) of 68 mA and the temperature of the diode was held at 25°C by a temperature controller (Thor Labs, TED 200C). The sinusoidally modulated light was delivered to a phantom through a 200 μm diameter, 3 m long optical fiber that was bundled to overfill the modes. Light was detected with a 1000 μm diameter, 2 m long optical fiber, also overfilled. The detected signal was focused onto an avalanche photodiode, APD, (ThorLabs, APD 210) where it was converted to voltage and fed back into the network analyzer. 101 measurements at 100 MHz were collected. The phase of the detected signal was recorded with LabView. The phase was measured at 5, 10, 20, 30, 40, 50 & 55 mm in each of three polyurethane phantoms, the phase was recorded at each distance on three separate occasions. The source fiber was imbedded in the phantom 9 mm from the top and 5 mm from the curved edge and emitted 3 mW of light. The detector fiber was rotated around the phantoms 9 mm from the top.

Further author information: (Send correspondence to S.A.P.)

S.A.P.: E-mail: prahl@bme.ogi.edu, Telephone: (503) 216-2197, 9205 SW Barnes Rd., Portland, OR 97225, USA

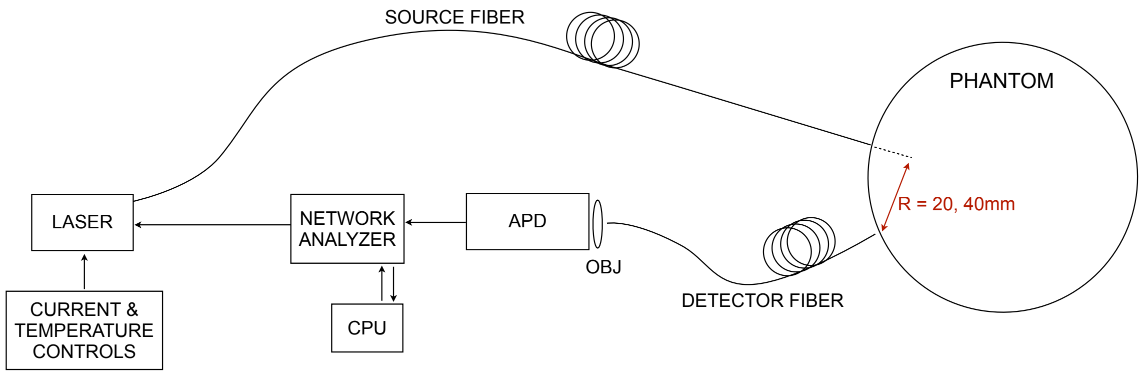

Figure 1: System used to measure the phase lag that develops between the source fiber (within the phantom) and the detector fiber (on the edge of the phantom) at $R = 20$ & $40\,\text{mm}$. These two measurements were used to calibrate to the medium.

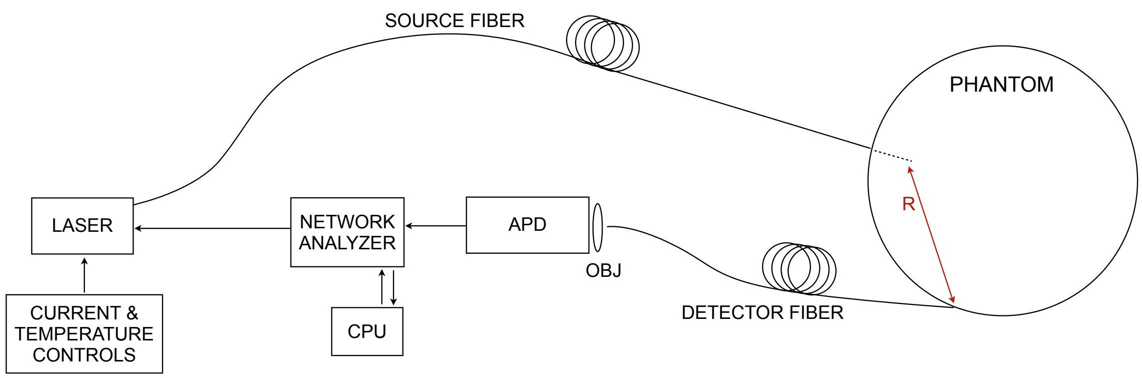

Figure 2: System used to measure the distance between the source fiber (within the phantom) and the detector fiber (on the edge of the phantom) at distances between 10–50 mm.

2.2 Analysis

Frequency domain measurements are based on sinusoidally modulating a light source. Upon photon propagation through scattering material, the sinusoidal signal becomes demodulated, both the amplitude (AC) of the wave and the average intensity (DC) decrease and a phase lag develops between the source wave and the propagating wave. The basis of the frequency domain (FD) theory is the Boltzmann Transport Equation which describes Linear Transport Theory.[1] For FD the diffusion approximation to the Boltzmann equation is used.[2] Due to the temporal and spatial broadening assumptions in the diffusion approximation, it holds true when scattering events are much more common than absorption events and when photons have propagated some distance from the source. The diffusion approximation has been shown to be accurate beyond one mean free path[3] and for $\mu_s' \gg \mu_a$and is given by:[2]

$$S(r,t) = \frac{1}{c}\frac{\delta}{\delta t}\phi(r,t) - D\nabla^2\phi(r,t) + \mu_a\phi(r,t) \tag{1}$$

Where $S(r,t)$ is the photon source, c is the speed of light in medium, $\phi(r,t)$ is the fluence rate, $D = \frac{1}{3(\mu_s'+\mu_a)}$, μ_a is the absorption coefficient and μ_s' is the reduced scattering coefficient and equals $\mu_s(1-g)$ where g is the anisotropy and μ_s is the scattering coefficient. For an isotropic short pulse point source in an infinite homogeneous medium, the source can be approximated by a delta dirac function and the fluence rate can be solved.[2] If the

Figure 3: The three polyurethane phantoms with optical properties similar to tissue in the near infrared. Each phantom is 6 cm in diameter and 10 cm high. Left to right phantoms are identified as 1, 2, &3.

source is modulated, the Fourier transform of the delta dirac function can be used to solve for the fluence and the phase of the fluence is then given by[4]

$$\theta(r,\omega) = -r\sqrt{\frac{b}{\alpha}}\left(1+\frac{\omega^2}{b^2}\right)^{1/4}\sin\left(\frac{1}{2}\tan^{-1}\frac{\omega}{b}\right) \tag{2}$$

where $b = \mu_a c$, $\alpha = Dc$, and $\omega = 2\pi f$. The expression for the phase shift may be further simplified for relatively low modulation frequencies $\omega \ll \mu_a c$. When $\mu_a \approx 1\,\mathrm{mm}^{-1}$ this means $f \ll 500\,\mathrm{MHz}$. For such modulation frequencies, the relation for the phase shift can be approximated as

$$\theta = -R\cdot\gamma\cdot\frac{\omega}{2c} \tag{3}$$

The phase measurements at all distances, R, and the derived calibration factor, $\gamma = \frac{1}{\sqrt{\mu_a/D}}$, were used to predict the distance the light had traveled. Residuals were calculated by subtracting the predicted distance from the known distance. The low frequency approximation, Equation 3 for the phase, θ, at 100 MHz at R= 20 & 40 mm was used to determine the calibration factor γ.

2.3 Characterization

Polyurethane phantoms were made with titanium dioxide (Dupont, Ti-Pure) and India ink (Speedball). Thin disks of the same polyurethane as the phantoms were measured using an integrating sphere technique to determine their optical properties.[5] Each disk was measured three times.

3. RESULTS & DISCUSSION

3.1 Optical Properties

The absorption coefficient of the phantoms was $0.002\,\mathrm{mm}^{-1}$ for all three phantoms with a standard deviation of $0.001\,\mathrm{mm}^{-1}$. The reduced scattering coefficient was 0.1, 0.5, & $1.0\,\mathrm{mm}^{-1}$ for phantoms 1, 2, & 3 respectively with a standard deviation of $0.01\,\mathrm{mm}^{-1}$ as shown in Table 1.

phantom	μ_a [mm^{-1}]	μ_s' [mm^{-1}]
1	0.002	0.1
2	0.002	0.5
3	0.002	1.0

Table 1: Optical properties of the phantoms as measured by the integrating sphere technique.

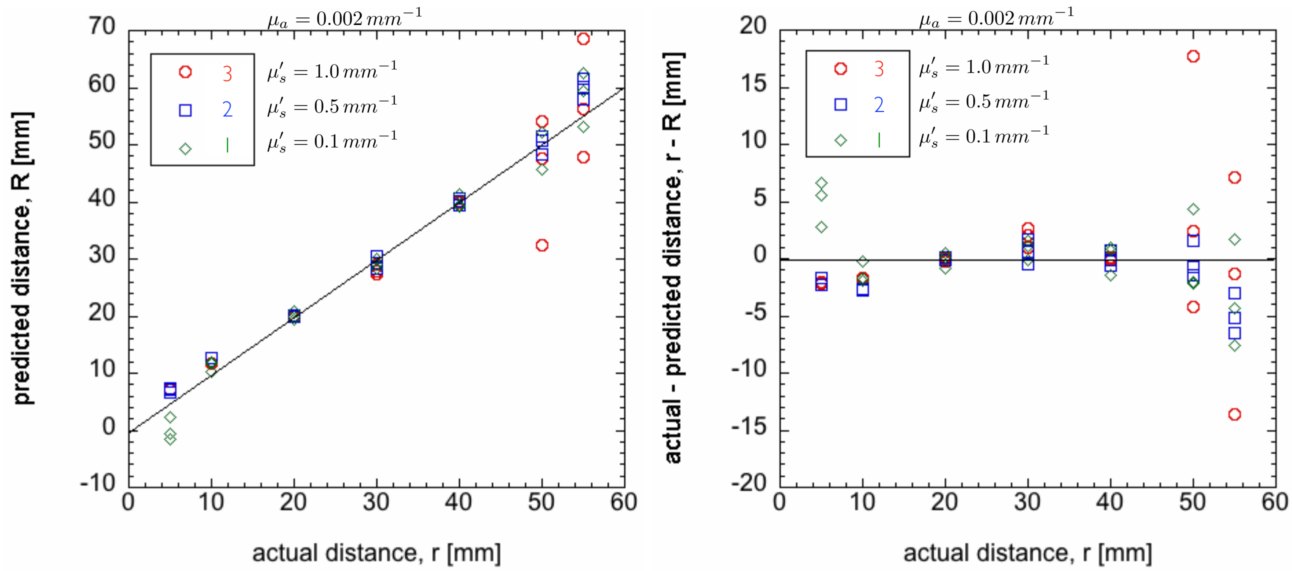

Figure 4: *Left:* The predicted distance plotted against the actual distance for each of the phantoms. The line is where the predicted distance equals the actual distance, $R = r$. *Right:* Residuals, the difference between the predicted distance and actual distance.

3.2 Distance Measurements

The predicted distance, R, is plotted a function of the actual distance, r, between source and detector as well as the residuals in Figure 4 for each of the three phantoms tested. The 20 & 40 mm locations were tightly grouped and indicated the accuracy of detector placement between each experiment. An error of 10% was considered acceptable and was achieved with exceptions as follows. The error above 50 mm was greater than 10% in all three phantoms due to a decrease in the signal to noise ratio. In the low scattering phantom, 1, the error at 5 mm was $\approx$ 100% and represented the lower limit of the technique. In the high scattering phantom, 3, a 10% error existed at 50 mm and represented the upper limit of the technique. The residuals were not randomly distributed around zero, however the trend may be explained by either a boundary condition that is not being accounted for in the model or a systematic experimental error of the actual distance, r, measured between source and detector.

4. CONCLUSION

We have demonstrated a simple method to measure the distance between an intensity modulated light source and detector in turbid media based on the proportionality of the phase lag and the distance. The limits of the technique were evident for distances less than 5 mm, particularly when $\mu_s' < 0.1\,\mathrm{mm}^{-1}$ and distances greater than 55 mm for the phantoms studied. This method may prove useful in industry and medicine as a non-destructive way measure distance through light scattering media.

The authors would like to thank the Safeway Foundation for funding this research

REFERENCES

1. K. M. Case and P. Zweifel, *Linear Transport Theory*, Addison-Wesley Publishing Co., 1967.
2. M. Patterson, B. Chance, and B. Wilson, “Time resolved reflectance and transmittance for the noninvasive measurement of tissue optical-properties,” *Applied Optics* **28**, pp. 2331–2336, Jun 15 1989.
3. L. Wang and S. Jacques, “Sources of error in calculation of optical diffuse reflectance from turbid media using diffusion theory,” *Computer Methods and Programs in Biomedicine* **61**, pp. 163–170, 2000.

4. M. Patterson, “Principles and applications of frequency-domain measurements of light propagation,” in *Optical-Thermal Response of Laser-Irradiated Tissue*, A. Welch and M. vanGemert, eds., Plenum Press, New York, 1995.
5. T. Moffitt, Y. Chen, and S. Prahl, “Preparation and characterization of polyurethane optical phantoms,” *Journal of Biomedical Optics* **11**, p. 041103, July/August 2006.