

Two-layer model for measuring the optical properties of turbid materials based on spatially resolved hyperspectral diffuse reflectance images

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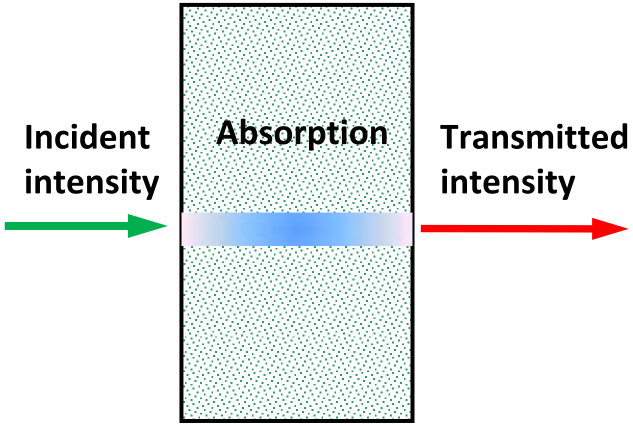
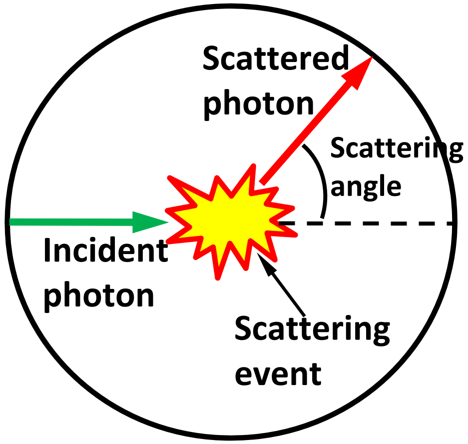
Overview

- Background
- Objective
- Theory and experiment
- Results
- Conclusions

Background





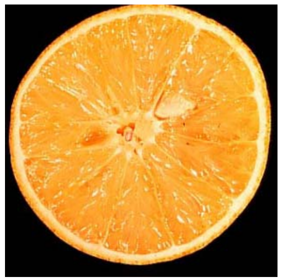
Optical properties

Absorption (μ_a): concentration of chemical components (sugar, protein, moisture, chlorophyll)

Scattering (μ_s): tissue structure (cell, intracellular bond, extracellular matrices)

Fruit

Two homogenous layers: skin and fresh



Vo-Dinh (2003)

Objective

Develop a nondestructive method to determine the absorption and scattering properties of two-layer turbid materials.

- Assess the two-layer diffusion model for describing light propagation;
- Perform sensitivity analysis and develop an inverse algorithm;
- Validate the diffusion model and inverse algorithm using Monte Carlo simulation and model samples.

Theory

Two-layer diffusion model for light propagation

Assumptions:

1) light scattering is dominant, semi-infinite

2) an infinitely small light beam

3) $L > \left[z_0 = 1/(\mu_{a1} + \mu_{s1}') \right]$

Diffusion model:

$$\begin{cases} D_1 \nabla^2 \Phi_1(\mathbf{r}) - \mu_{a1} \Phi_1(\mathbf{r}) = -\delta(x, y, z - z_0) & 0 \le z < L \\ D_2 \nabla^2 \Phi_2(\mathbf{r}) - \mu_{a2} \Phi_2(\mathbf{r}) = 0 & L \le z \end{cases}$$

B.C.

$$\begin{cases} \phi_1(-z_b, s) = 0 \\ \phi_2(\infty, s) = 0 \\ \dfrac{\phi_1(l,s)}{\phi_2(l,s)} = \dfrac{n_1^2}{n_2^2} = 1 \\ D_1 \left. \dfrac{\partial \phi_1(z,s)}{\partial z} \right|_{z=l} = D_2 \left. \dfrac{\partial \phi_2(z,s)}{\partial z} \right|_{z=l} \end{cases}$$

r: $\mathbf{r} = (x, y, z)$ **;**

Φ_i : fluence rate of layer i;

D_i : diffusion constant

($D_i = 1/[3(\mu_{ai} + \mu_{si}')]$);

μ_{ai} : absorption coefficient;

μ_{si}' : reduced scattering coefficient;

L: thickness of the first layer.

Kienle, et al. (1998)

Theory

$R(r)$ is obtained from the integration of radiance over the solid angle accepted by the fiber

$$R(r) = 0.118\Phi_1(r, z=0) + 0.306 D_1 \frac{\partial}{\partial z}\Phi_1(r,z)\Big|_{z=0}$$

$$R(r) = 0.118 f(r, \mu_{ai}, \mu_{si}', L) + 0.306 g(r, \mu_{ai}, \mu_{si}', L)$$

Independent variable: Distance (r)
Dependent variable: Reflectance (R)
Parameters: optical parameters and thickness $(\mu_{a1}, \mu_{s1}', \mu_{a2}, \mu_{s2}', L)$

Inverse algorithm

Nonlinear least squares

$$\min_x \frac{1}{2}\left\|F(x, xdata) - ydata\right\|^2 = \frac{1}{2}\sum_{i=1}^{m}(F(x, xdata_i) - ydata_i)^2$$

Scaled sensitivity coefficients

$$R_{\mu_{ai}} = \mu_{ai}\frac{\partial R}{\partial \mu_{ai}}$$

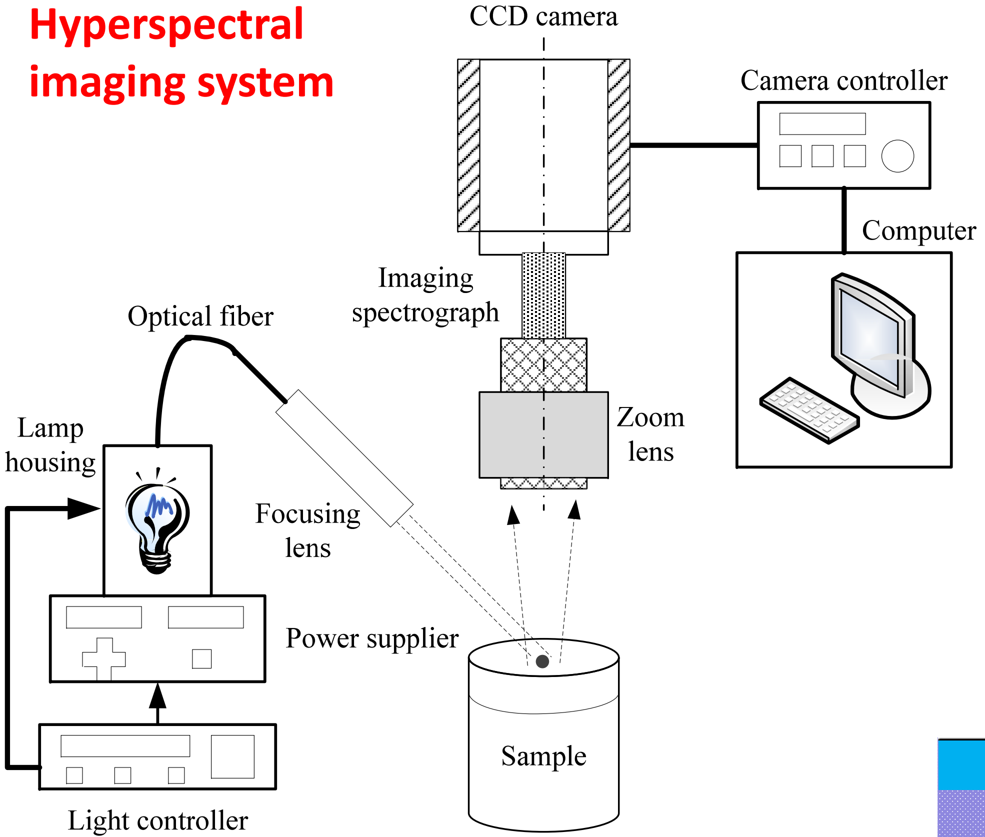
$$R_{\mu_{si}'} = \mu_{si}'\frac{\partial R}{\partial \mu_{si}'}$$

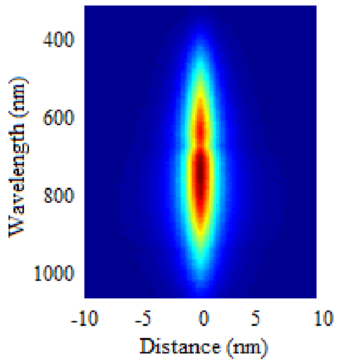
Beck, et al. (1977)

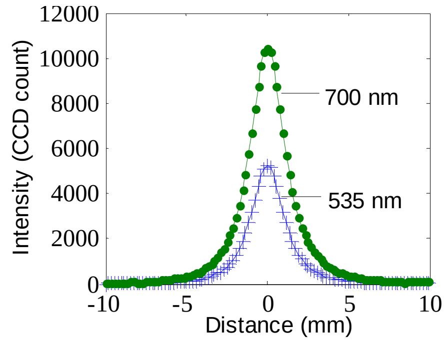
Experiment

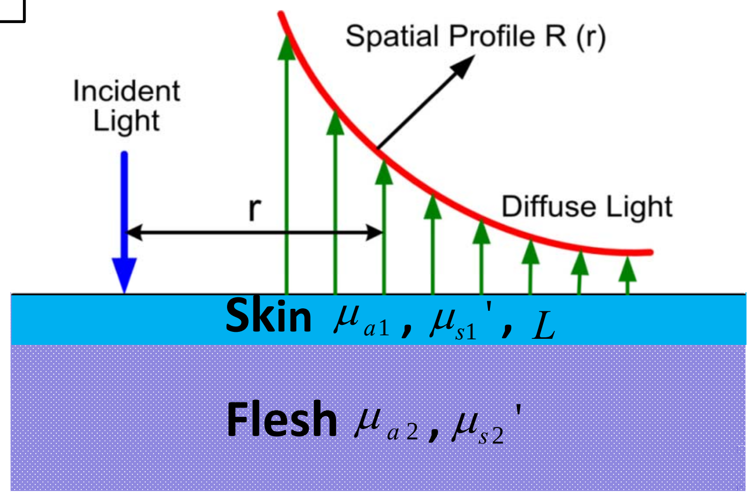
Spatially resolved steady-state technique

Hyperspectral imaging system

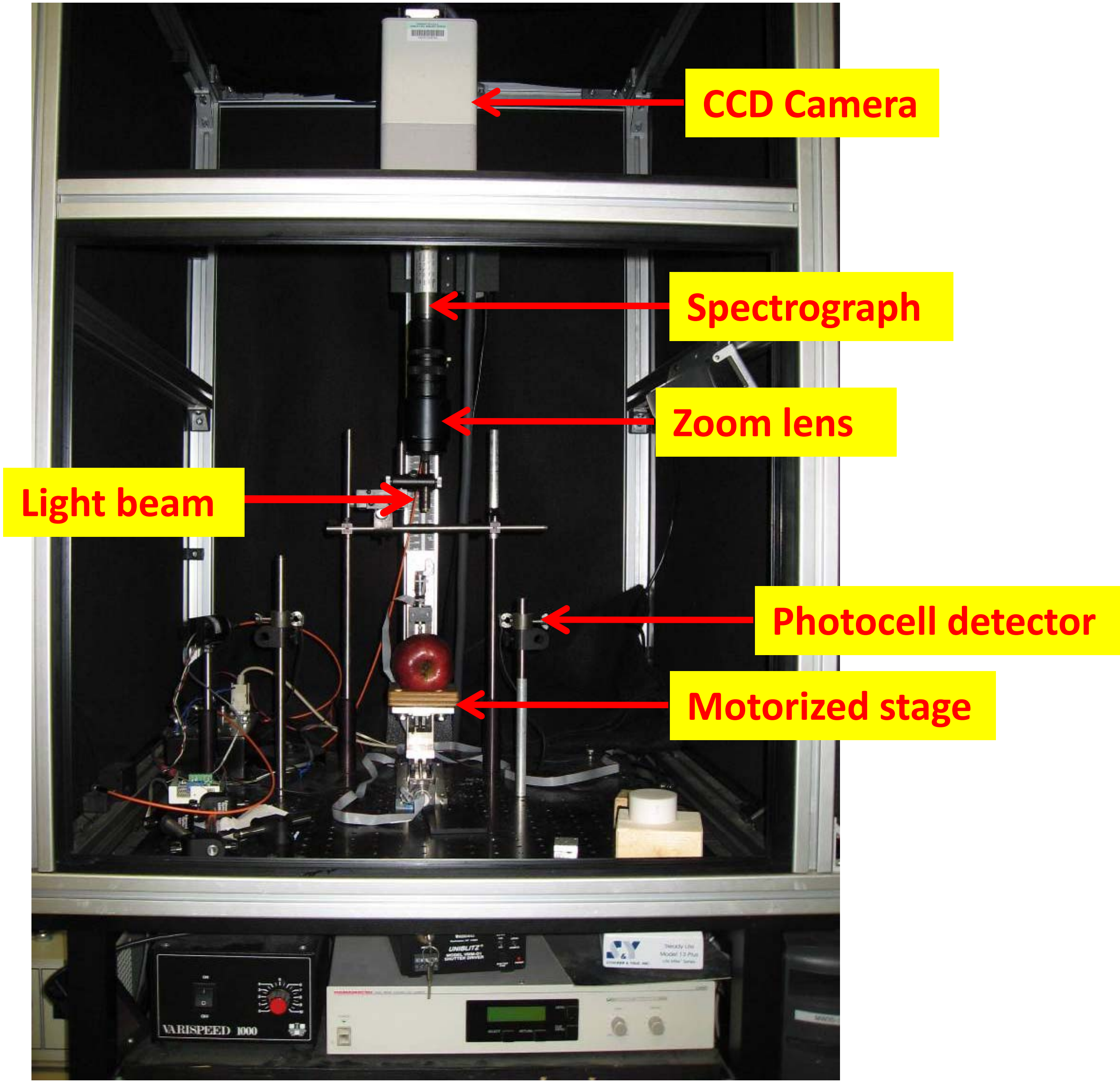








Experiment


CCD Camera
Spectrograph
Zoom lens
Light beam
Photocell detector
Motorized stage
VARISPEED 1000

Experiment

- **Model and algorithm validation**

Monte Carlo simulation (MCML):

Compare reflectance from MCML and two-layer diffusion model;

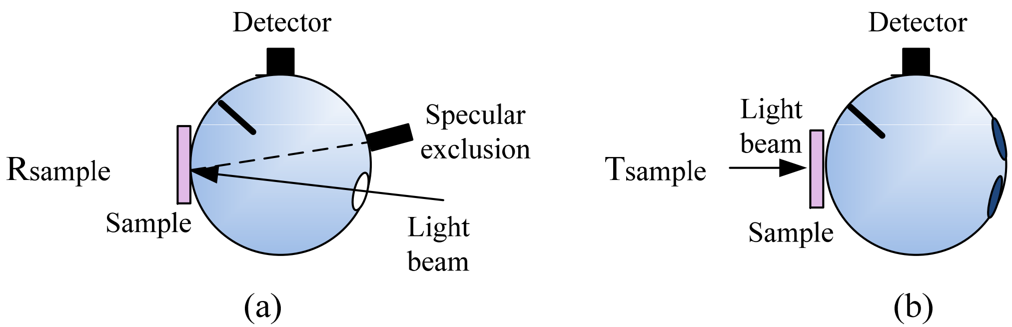
Estimate two parameters;

Estimate four parameters.

Experiment validation:

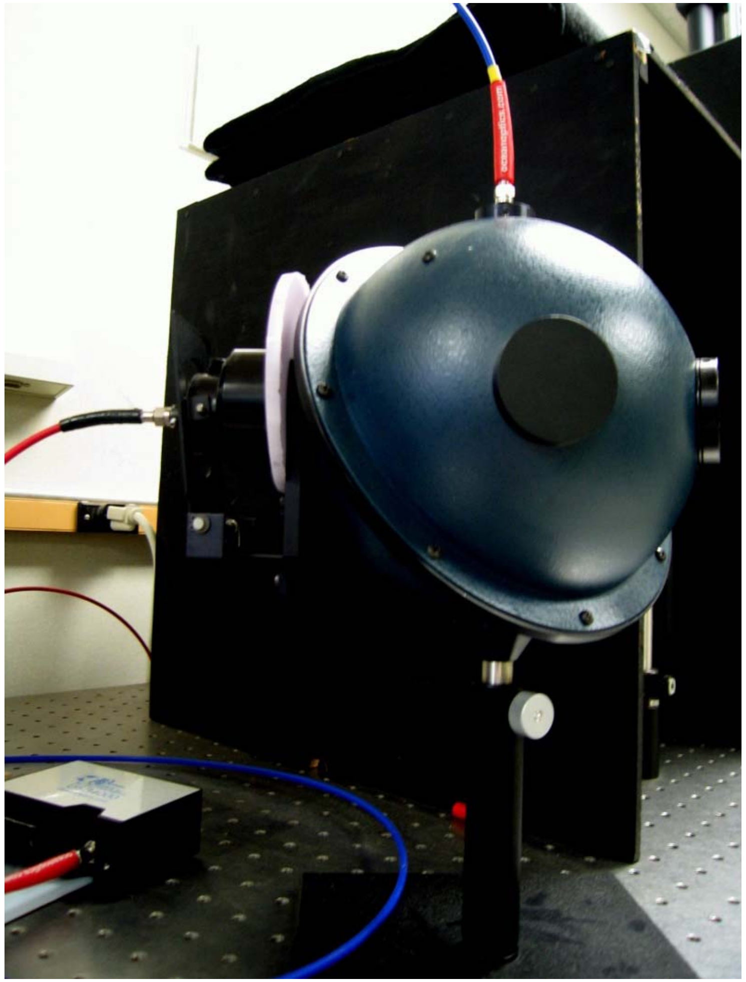
Model samples consisted of silicone, blue dye, and aluminum oxide;

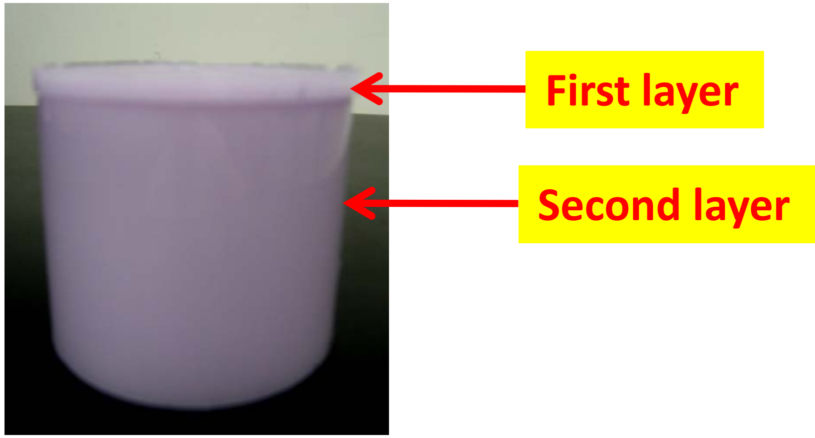
Standard method to measure optical properties: integrating sphere.



Wang, et al. (1995)
Prahl, et al. (1993)

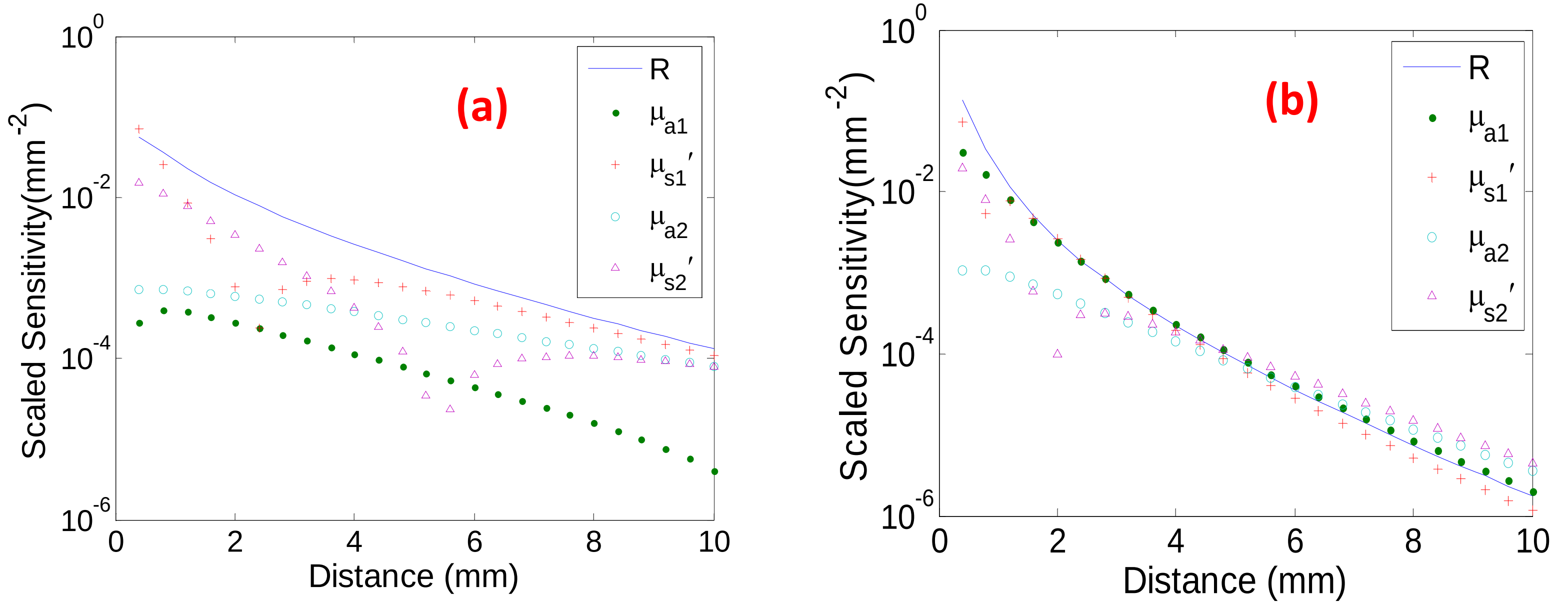
Experiment





Results

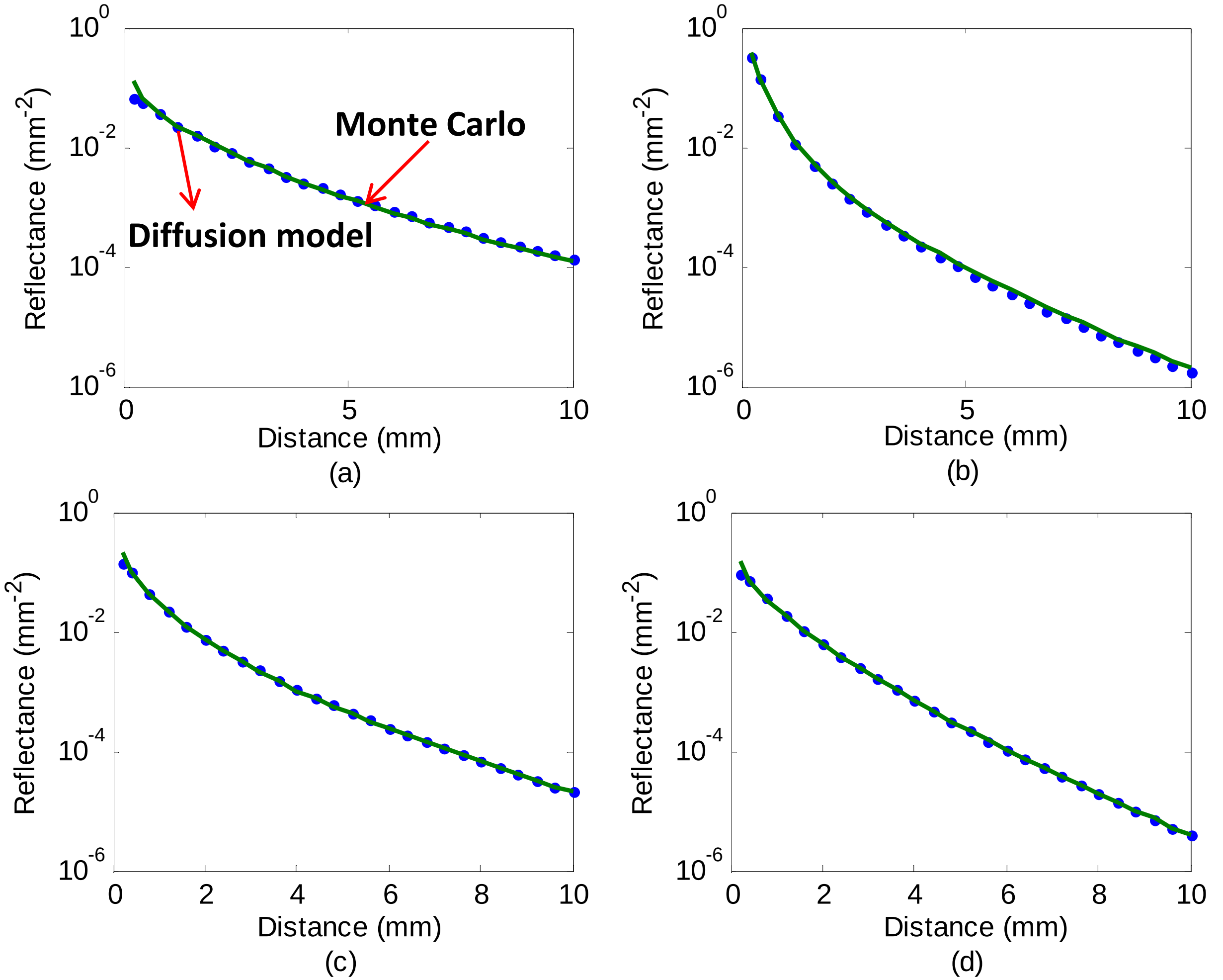
Scaled sensitivity coefficients as functions of source-detector distances



(a) $\mu_{a1}/\mu_{a2} = 0.50$ and $\mu_{s1}'/\mu_{s2}' = 0.86$; (b) $\mu_{a1}/\mu_{a2} = 6.50$ and $\mu_{s1}'/\mu_{s2}' = 1.80$;

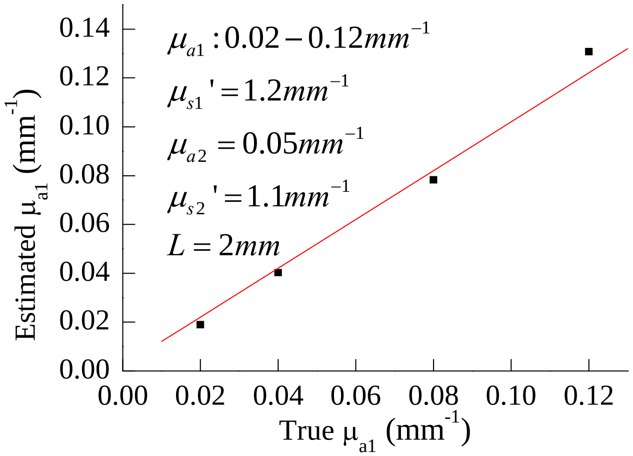
Results

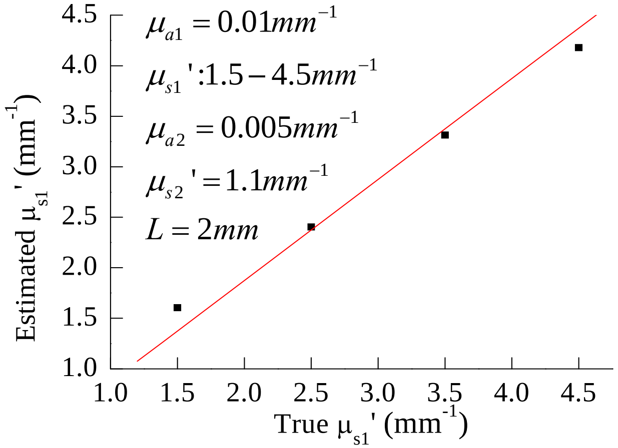
Comparison of diffuse reflectance obtained from the two-layer diffusion model and Monte Carlo simulation

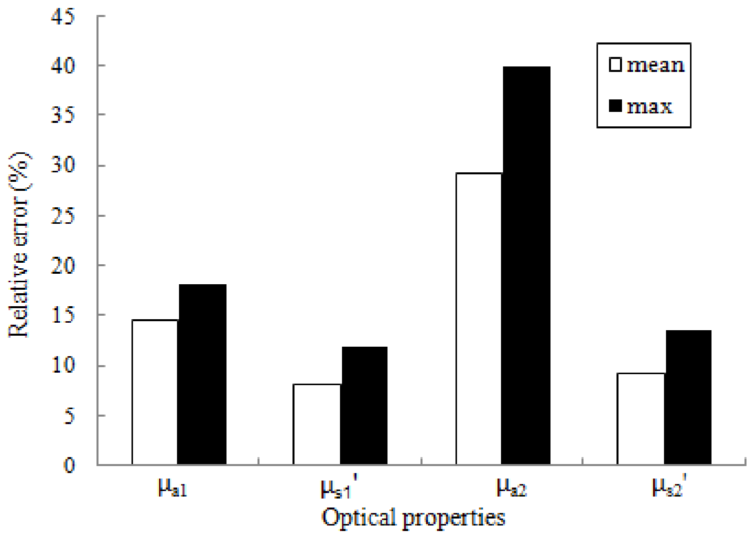


Results

Estimated absorption and reduced scattering coefficients from fitting the diffusion model to MC data







Two parameters estimation

Average error:

4.2% for μ_{a1}, 4.1% for μ_{s1}'

four parameters estimation

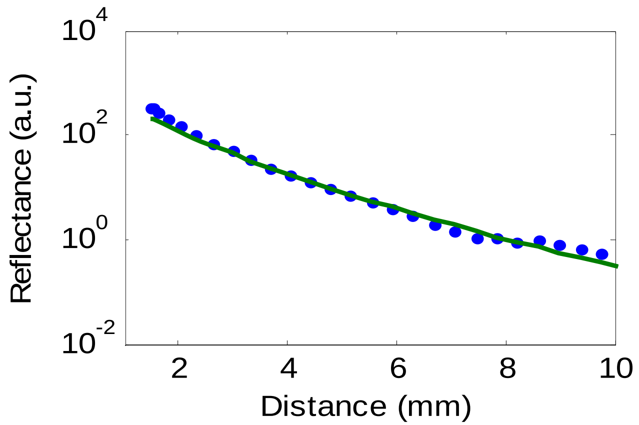
Average error:

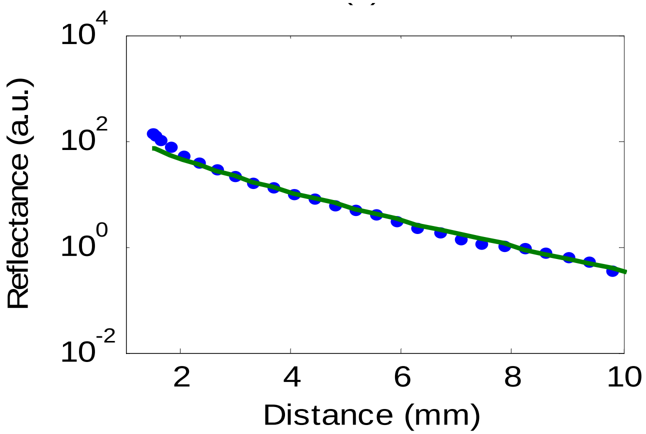
14.5% for μ_{a1}, 8.1% for μ_{s1}',

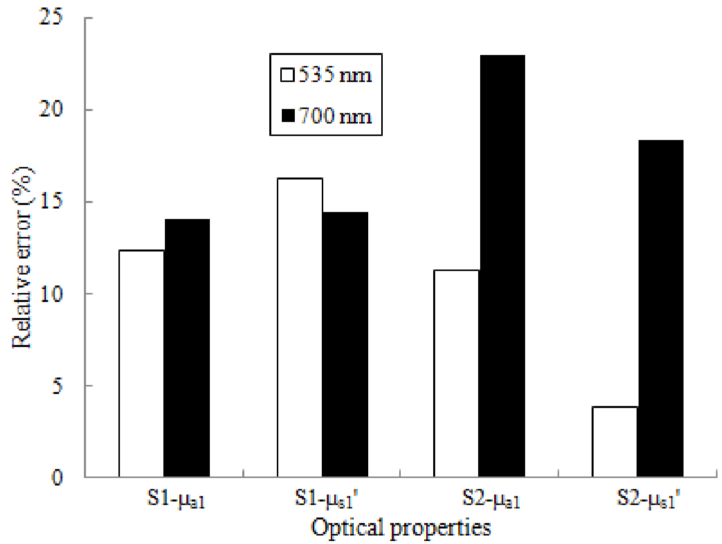
29.3% for μ_{a2}, 9.1% for μ_{s2}'

Results

Model validation by model samples







Relative error:

μ_{a1}**: 11.3-23.0%**

$\mu_{s1}{}'$**: 3.8-18.4%**

Conclusions

- The diffusion model accurately describes light propagation in two-layer turbid media;
- The inverse algorithm gives good estimates of optical parameters based on MCML data;
- Reasonable results for estimating optical parameters were obtained from the model samples;
- The spatially resolved technique is promising for determining optical properties of two-layer materials;
- Further work is needed on optimizing the hyperspectral imaging system and improving the inverse algorithm.

Thanks for your attention!

Questions?