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Examining Single Scattering Region in Concentration, Depth, and Wavelength on Diluted Media

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It is often assumed that single scattering is dominant in diluted media. However, the assumption could not be valid depending on the concentration and the depth of the media and the wavelength of light. In this paper, we develop a method to examine the single scattering region, where the assumption is valid, through spectral measurements for different concentrations and depths of a medium. Finally, we examine the single scattering region on several media experimentally.

1. Introduction

There are many kinds of scattering media around us, e.g., milk and juice. When scattering properties of the media are experimentally analyzed, they are often diluted to where single scattering seems to be dominant [1]. However, an appropriate concentration of the diluted medium is not clear because it depends on the wavelength of light and the depth of a cuvette (media depth). This paper presents a method to examine the single scattering region, where the single scattering is dominant, in the concentration and the depth of a diluted medium and the wavelength of light.

2. Principle

In the single scattering region, an intensity of light is supposed to be attenuated exponentially as

$$I(\lambda) = I_0(\lambda)e^{-\sigma(\lambda)cd}, \tag{1}$$

where I and I_0 correspond to the transmitted and incident intensity, respectively, $\sigma(\lambda)$ is the extinction coefficient, which represents the degree of attenuation per unit depth and concentration at a wavelength λ, and c and d are the concentration and the depth of the medium, respectively. From Eq. (1), $\sigma(\lambda)$ is obtained as

$$\sigma(\lambda) = -\frac{1}{cd}\log\frac{I(\lambda)}{I_0(\lambda)}. \tag{2}$$

Because $\sigma(\lambda)$ is independent of both concentration and depth, $\sigma(\lambda)$ must be constant at each wavelength, theoretically. However, when the single scattering is not dominant, Eq. (1) is not hold, and $\sigma(\lambda)$ calculated by Eq. (2) is not constant. Therefore, we use $\sigma(\lambda)$ to examine the single scattering region. When the reference coefficient $\sigma_R(\lambda)$ is given where the single scattering is dominant, the single scattering region can be examined by checking whether the coefficient $\sigma(\lambda)$ is same as $\sigma_R(\lambda)$ or not at a certain concentration and depth.

3. Experiment and Discussion

We conducted an experiment to examine the single scattering region. Figure 1 illustrates the experimental setup used in this experiment. The target scattering media are regular milk and soymilk, which are diluted to a certain concentration with water: concentrations are 0.03% to 1.0%. By adjusting the amount of the media in a glass tank, we changed the depth to 10mm, 20mm, and 40mm. For spectral measurements, we use a hyperspectral camera whose spectral sensitivity is in 500 to 900nm and a collimated halogen light source having a wide spectrum. We examined the single scattering region by calculating $\sigma(\lambda)$ by Eq. (2) for each wavelength λ. Figure 2 shows $\sigma(\lambda)$ of regular milk at various concentrations and light pass depths. In Fig. 2 in 40mm depth, $\sigma(\lambda)$ in 0.03% to 0.25% are constant for all wavelengths, however, $\sigma(\lambda)$ in 0.5% to 1.0% are not in short wavelength.

We determine a reference coefficient $\sigma_R(\lambda)$ to examine the single scattering region. In this paper, we use the average of $\sigma(\lambda)$ of 10 to 40mm depth at 0.13% concentration as the reference coefficient $\sigma_R(\lambda)$. Figure 3 illustrates the relative error of the coefficient, which is defined as $\frac{|\sigma-\sigma_R|}{\sigma_R}$. The upper and lower graphs are the results of regular milk and soymilk, respectively. The colors represent the value of error: Blue ($\sim$0) indicates that $\sigma(\lambda)$ is close to $\sigma_R(\lambda)$, which can be interpreted as in the single scattering region. Meanwhile, the regions colored with green to red have larger error than the blue regions. From Fig.3, one can see that the regions in high concentration, large depth, and short wavelength have large error that indicates out of the single scattering region. Indeed, observed light intensities were enhanced by in-scattering that the light comes back by multiple scattering, and stronger in-scattering occurred in shorter wavelength. Figure 3 also shows that the region in low concentration and small depth is noisy. It would be caused by poor signal-to-noise ratio since the attenuation by scattering is too small.

4. Conclusion

In this paper, we proposed a method to examine the single scattering region through spectral measurements for different concentrations and depths of a medium. We experimentally examined the single scattering region on two media. As the results, the single scattering region is clearly visualized and we could see appropriate concentrations and depths for wavelengths where we can assume that the single scattering is dominant.

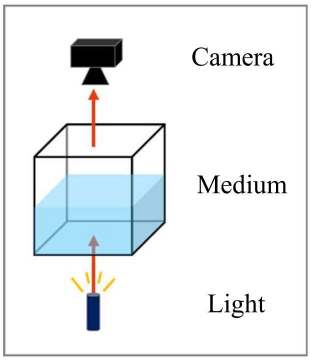
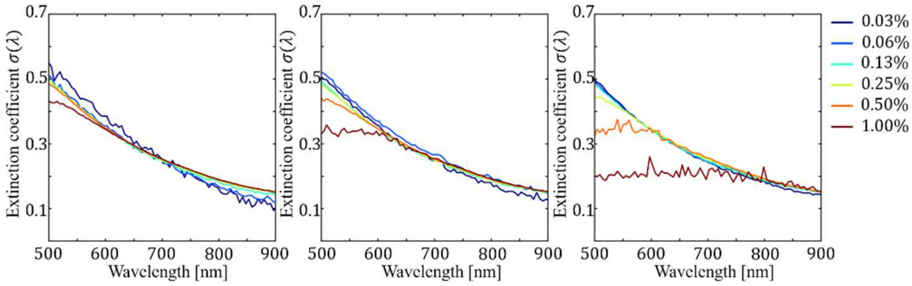
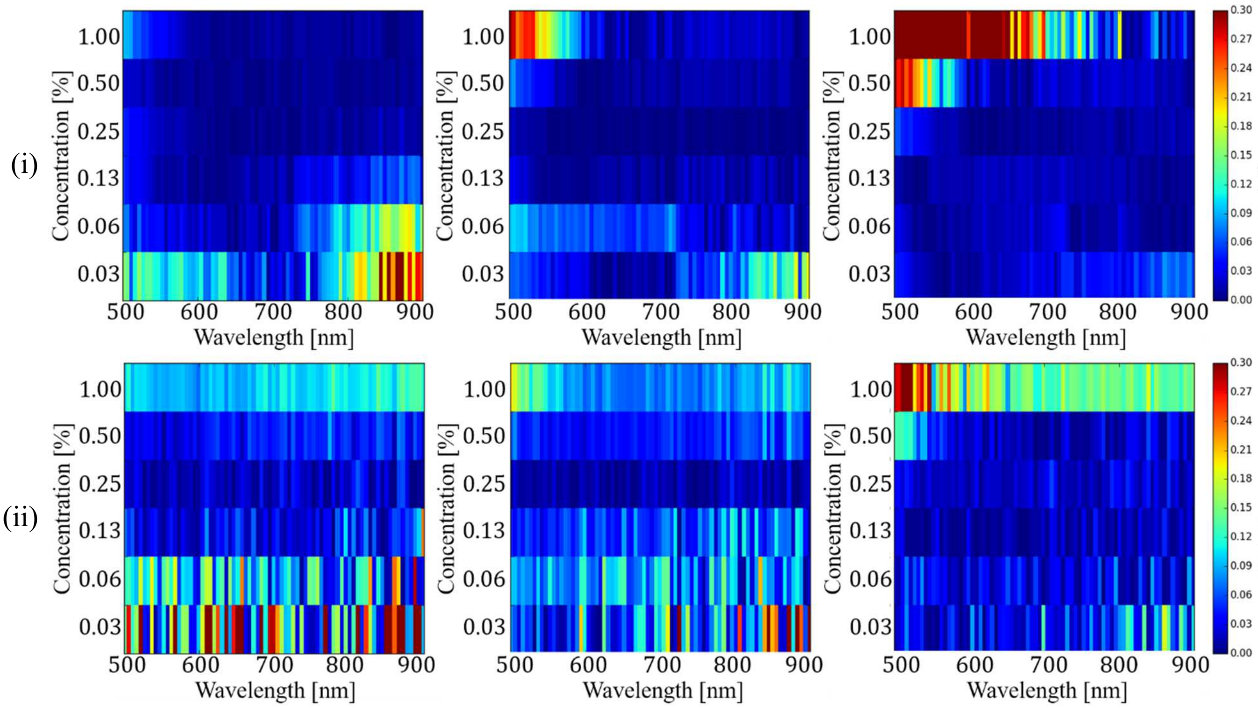


Figure 1. Experimental setup



(a) Depth 10mm (b) 20mm (c) 40mm

Figure 2. Extinction coefficient $\sigma(\lambda)$ at various concentrations where light pass depths are (a):10mm, (b):20mm, and (c)40mm.



(a) Depth 10mm (b) 30mm (c) 50mm

Figure 3. Relative error $\frac{|\sigma-\sigma_R|}{\sigma_R}$ for various concentrations, wavelengths, and depths.
(i): Regular milk, (ii): Soymilk

Acknowledgement

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Reference

[1] Narasimhan, S. G., *et al*. Acquiring scattering properties of participating media by dilution. *ACM Trans. on Graphics,* 25(3), 2006.