Abstract of Doctoral Dissertation

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Title of Doctoral Dissertation

STUDY OF SPECTRO-POLARIMETRIC BIDIRECTIONAL REFLECTANCE PROPERTIES OF LEAVES

（スペクトル及び偏光を考慮した葉の双方向反射率特性の研究）

The reflectance of the leaf consists not only of its intensity but also of polarization and the polarization techniques are generally used for separating specular reflectance from diffuse reflectance. The internal diffuse component of the spectral reflectance contains the details of the biochemical properties of plant, activity of photosynthesis, expected amount of harvest, and water condition. Specular reflectance of the leaf strongly depends on a combination of the angle of incidence of the light source and the angle of observation view. The leaves look shiny at the shallow angle, where the most of this reflection is polarized from the surface of leaves. Although the leaf spectral reflectance which is a point of convergence for many types of research, the study of spectral measurement with polarization in a single leaf is largely unexplored.

This dissertation aims to connect the polarization techniques and directional relations of the leaf Bidirectional Reflectance Distribution Function (BRDF) by differentiating specular and diffuse reflectance. To do this, the estimation of single leaf BRDF of Coffea canephora Pierre (Coffee), Epipremnum aureum (Pothos), and Fragaria × ananassa (Strawberry) was carried out based on the measurements by Liquid Crystal Tunable Filter (LCTF) camera in the wavelength range of 460-780 nm with a linear polarizer. The imaging with the multispectral LCTF camera has a great advantage in measuring a selected leaf area with an arbitrary size of the field of view. There are hundreds of combinations of incident light and observation direction in single leaf Bidirectional Reflectance Factor (BRF) measurement. In order to conduct the measurements for all those conditions, we built the automatic goniometer with LCTF camera in a laboratory.

The analysis of the measured data shows unpolarized reflectance has a strong correlation with PROSPECT model and that it can be possible to separate these light reflections with any spectral measurement device using a rotating polarizer. Polarized reflectance strongly depends on relative azimuth ϕ and zenith view θ_r angles and the unpolarized part is almost independent at that illumination angle relatively. The leaf DHRF in a field measurement has been difficult to determine in real life since the integrating sphere is needed or the hundreds of leaf BRF measurement is required at the outside. If a method of stabilizing is existed, it is possible to quickly determine the biochemical contents of the leaves using the PROSPECT model in a field. The results of this study show that spectro-polarimetric measurement is able to do that. Mirror reflections of all leaves were measured from 3.6^o to 68.4^o with an accuracy of 1.8^o for estimating surface roughness. It was found that an optimal surface roughness of about 46.1 nm is obtained for pothos leaves, which is almost twice compared to strawberry leaves. The maximum rms of surface roughness is 71.67 nm for pothos leaves, 92.41 nm for strawberry leaves. The smoothest surfaces of leaves are pothos, and the roughest are strawberry leaves in the plants we measured. Although the surface

roughness of strawberry is considerably higher than for pothos, the light penetration into the leaves is equal for all plants at same wavelengths.

In previous studies, the leaf BRF prediction is usually based on the Cook-Torrance (Cook and Torrance, 1981) prevalent model in computer graphics assuming that the surface micro-geometry acts as a set of specular mirrors. Another type of models are widely used in the optics community, computing diffraction effects caused by differences in height in the surface micro-geometry and predicts visual appearance from the frequency content of the height distribution. The Cook-Torrance model may not be suitable for the leaf reflectance in our observation because the surface roughness cannot be determined by the actual measurement. The Generalized Harvey-Shack (GHS) scattering theory is well studied from rebound models determined by height distribution (Krywonos, 2006) and the GHS theory is not limited to any special wavelength range and RMS roughness value. Spectro-polarimetric measurement results and physical scattering theory have led us to create a new reflectance model. We successfully created a new leaf bidirectional reflectance model which considers that the diffuse component is Lambertian inside of the leaves and an internal scattering coefficient is calculated to an output value of PROSPECT model; the specular component is explained by GHS scattering theory. The polarization property of reflected light on a single leaf is also identified and rebuild bidirectional reflectance factors including polarized, unpolarized, and the total reflectance factors according to our model in this dissertation. Finally, a new spectro-polarimetric bidirectional method is more controllable for the BRF pattern of a single leaf.