# Indicatrices of the leaves of various woody plant species

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## Abstract

The indicatrices of the leaves of various woody plant species are measured by use of a goniophotometer. Minnaert constants calculated from these indicatrices are used for their quantitative evaluation. From the results of the measurement, we have found that the characteristics of light scattering from some of the leaves follow Lambertian law and that those of the others don't. It is discussed why the light scattering from leaves does not obey Lambertian law.

Key words ; Leaf, Indicatrix, Minnaert constant

## 1. Introduction

To estimate the environment of the earth's surface, multispectral remote sensing technology has been largely developed in recent years. There have been many reports on the identification and the detection of stress of vegetative canopies. In the multispectral remote sensing for the vegetated area, the fundamental and important data on the correlation between the incident light and the leaf canopies are acquired. Suits (1972) calculated the directional reflectance of a vegetative canopy. His model is an extension of the canopy model of Allen, Gayle and Richardson (1970) which, in turn, is an extension of Duntley (1942) equations that are, in turn, extension of the Kubelka-Munk equations(1948, 1954).

In a study on light scattering from leaf layers, the individual leaves are treated as perfect Lambertian diffuser. But there are various species of leaves in nature. Though Verhoef (1984) has discussed that the leaf on which the light scatters is a perfect Lambertian diffuser, does the light scattering from all of the leaves follow Lambertian law ? To solve this question we studied the indicatrices of leaves in various species. Table 1 is a list of the studied woody plants in scientific names and in local names as well as in Japanese names because they were collected in Japan. In the text they are referred to by local names which are more commonly used. Breece, H. T. III and Holmes, R. A. (1971) has reported the bidirectional scattering characteristics of healthy green soybean and corn leaves and Thomas W. Brakke (1989, 1993) has reported the non-Lambertian characteristics as to the reflection on the leaves according to seasons and bidirectional reflection characteristics. But we report non-Lambertian characteristics of various leaves by using Minnaert constants (M. Minnaert, 1941).

## 2. Indicatrix

We used a goniophotometer shown in Fig. 1 to measure the indicatrices. The halogen lamp is used as an optical source of the goniophotometer. The light from the optical source is collimated by a collimator lens, and enters on the leaf sample. The light from the sample is collected by a lens, and it reaches a photomultiplier through a filter. The signals from the photomultiplier are converted in an A/D convertor, and are processed by a personal computer. The optical flux 1.5 cm in diameter enters the leaf sample. The measurement was taken at each 5° of the scattering angle.

The indicatrix is a graph of the angular distribution representing the intensity of the scattered light from the surface of an object on the polar coordinate. Then an indicatrix shows in which angular direction and in what quantity the light from the surface is scattered. Minnaert constants are used for quantitative estimation of the indicatrices. Let the detecting angle and the incident angle be e and i, respectively. Detected radiance L is

$$L(\lambda, e) = L_n(\lambda) \cdot \cos^{k(\lambda)} i \cdot \cos^{k(\lambda)-1} e, \tag{1}$$

where k is Minnaert constant [10]. When i = e = 0°, $L_n(l)$ is an effective vertical response. In equation (1), when e = 0°,

$$L(\lambda) = L_n(\lambda) \cdot \cos^{k(\lambda)} i. \tag{2}$$

The value of k is estimated by regression analysis from (2). Equation (2) is written as follows ;

$$Log L(\lambda) = Log L_n(\lambda) + k(\lambda) Log \cos i. \tag{3}$$

Here by letting

$$Y = Log L(\lambda), \tag{4}$$

$$X = Log \cos i, \tag{5}$$

and

$$b = Log L_n(\lambda), \tag{6}$$

we obtain

$$Y = k(\lambda) \cdot X + b. \tag{7}$$

If k = 1.0, (2) becomes a Lambertian equation. The indicatrices obtained when k = 0.7, 1.0 and 2.0 are shown in Fig. 2. If k = 1. 0 the indicatrix becomes spheric, and when it is smaller than 1.0, the indicatrix swells outward, while when it is larger than 1.0, the indicatrix becomes slender.

The equation (2) is obtained when e is assumed to be 0° in equation (1), but in the experiment, the light vertically enters on the sample and the data are obtained not when e = 0°, but by varying the detecting angle. However if we assume the reciprocity law [11] of the scattering, the detecting angle is considered to be $0°$ when the incident angle is $0°$ . In this measurements, the illumination spot size is about 4 cm, and the aperture of a detector is 2 cm. A parallel beam is incident on the sample. The detector is set to detect the light from an infinite distance. Therefore it would be reasonable to represent indicatrices using Minnaert constants.

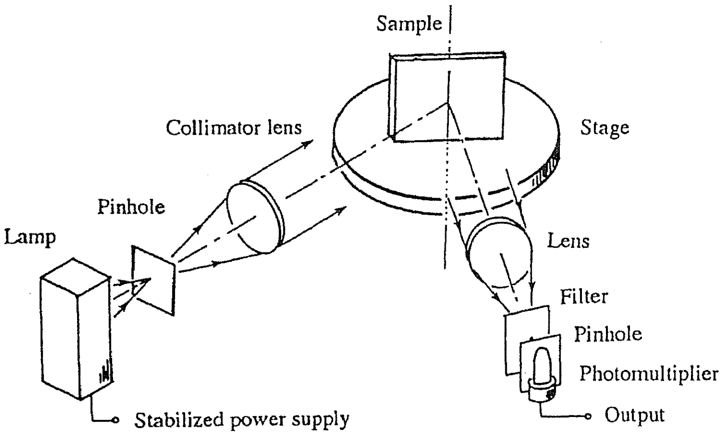


Fig. 1. Schematic diagram of the experimental equipment.

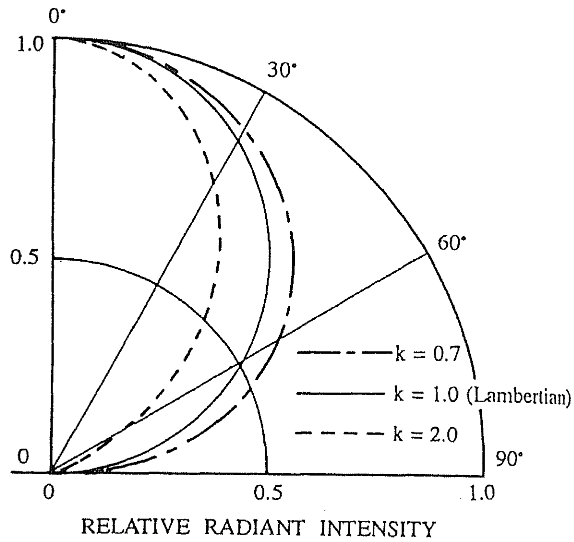


Fig. 2. Indicatrices obtained by calculation when the Minnaert constant k are 0.7, 1.0, and 2.0.

## 3. Experiments

Several experiments have been done by use of a goniophotometer shown in Fig. 1. The scientific names and local names as well as Japanese names of the leaves used in the experiment are shown in Table 1. First the indicatrices were measured in the case the detecting angle is zero degree. The incident angles into the sample are from $15°$ to $90°$ . The measurement points with Camellia and Cherry fit a $\cos^k\theta$ curve when Minnaert constant k=1.12. When k=1.42, they do

Table 1. Scientific names, local names, and Japanese names of woody plants used in the experiment.

| Scientific name | Species ( Local name ) | Japanese name |
|---|---|---|
| *Acer palmatum* | Japanese maple | Momiji |
| *Camellia japonica* | Camellia | Tsubaki |
| *Carpinus laxiflora* | Hornbeam | Akashide |
| *Carpinus japonica* | Japanese hornbeam | Kumashide |
| *Cedrus deodara* | Himalaya cedar (deodar) | Himarayasugi |
| *Cinnamomum camphora* | Camphor | Kusunoki |
| *Citrus tachibana* | Mandarin orange (tangerine) | Mikan |
| *Clethra barbinervis* | Clethra | Ryoubu |
| *Cornus florida* | Flowering Dogwood | Hanamizuki |
| *Diospyros kaki* | Japanese persimmon | Kaki |
| *Euonymus japonicus* | Spindle | Masaki |
| *Ginkgo biloba* | Ginkgo (maidenhair) | Icho |
| *Juniperus chinensis* | Sabina endlicher | Kaizukaibuki |
| *Nerium indicum* | Oleander | Kyouchikutou |
| *Pinus thunbergii* | Pine | Matsu |
| *Photinia glabra* | Chinese hawthorn | Kanamemochi |
| *Platanus orientalis* | Platan (sycamore) | Puratanasu |
| *Prunus × yedoensis* | Cherry | Sakura |
| *Sorbus commixta* | Mountain ash (rowan) | Nanakamado |
| *Stewartia pseudo-camellia* | Deciduous camellia | Natsutsubaki |
| *Styrax japonica* | Snowbell | Egonoki |
| *Viburnum odoratissimum* | Coral | Sangoju |
| *Zelkova serrata* | Zelkova | Keyaki |

not fit as is shown in Fig. 3. However, they fit well when the scattering angle is larger than 50° . The correlation coefficients and the experimental results are shown in Table 2. The number of times of measurements is 16. The measurement points fit the $\cos^k\theta$ curve when the correlation coefficient $R^2$ is near 0.98, but not when it is near 0.89. An indicatrix is obtained by connecting measurement points. Minnaert constants are obtained from these indicatrices. In Figs. 4 and 5, the curves called indicatrices are drawn by connecting the measurement points. We obtained Minnaert constant k from these curves. Nine samples of them with appropriate dispersion were selected and plotted on Figs. 4 and 5. The indicatrix shows the diffuse components of reflectance. Minnaert constant does not represent the total reflectance of a leaf, but represents the degree of the reflectance intensity in angular directions. Fig. 4 shows the indicatrices of **Pine, Himalaya ceder,** and **Sabina Endlicher** giving Minnaert constants smaller than unity, which are more swelling than the Lambertian curve. The characteristics of the first group including **Pine, Himalaya cedar** and **Sabina Endlicher** are that they have a mass of needle leaves. Thus the light is scattered in various directions and probably by that reason Minnaert constants are smaller than 1.0. Fig. 5 shows the indicatrices giving Minnaert constants larger than unity. The

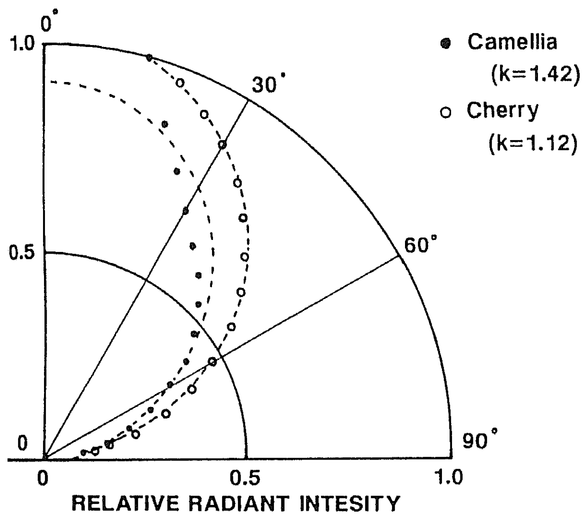


Fig. 3. Minnaert function $\cos^k\theta$ curves for Camellis and Cherry.

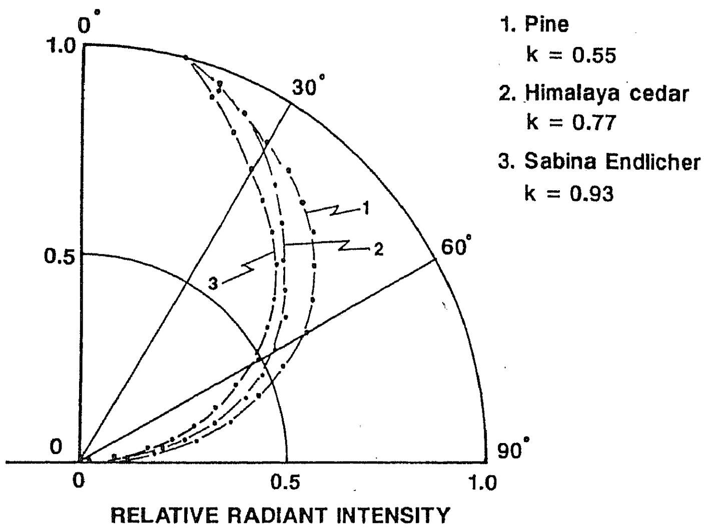


Fig. 4. Indicatrices of needle leaves of Woody plants.

photograph of a leaf of this classification is shown in Fig. 6 ( a ), which is **Himalaya cedar** (k = 0.77) and consists of small construction units. In the second group the leaves of Minnaert constants 1.05 to 1.09 shown in Fig. 6 ( b ) have a surface covered with downy hair, and for that reason, the light may be scattered uniformly. This photograph was magnified twenty times. Different from the others **Ginkgo (maidenhair)** leaves have no downy hair but fine tucks over the surface and therefore their Minnaert constant is as small as 1.07. The third group with Minnaert constants of 1.10 - 1.28 as is shown in Fig. 6 (c) include the leaves with a rough surface without downy hair and not very glassy. The leaves in the fourth group (Fig. 6 ( d )) carry the specular nature and Minnaert constants are larger than those in the other groups.

Next we measured the indicatrices when the incident angle is 45 degrees to the surface of the leaf. Experimental results are shown in Figs. 7. Fig. 7 was replaced by a new one which shows Minnaert constants of Platan (k=1.05), Cherry (k=1.12), Hornbeam (k=1.27) and Coral (k=1.57) as representative leaves in classification of Table 2. In the leaves with Minnaert constants of 1.05,

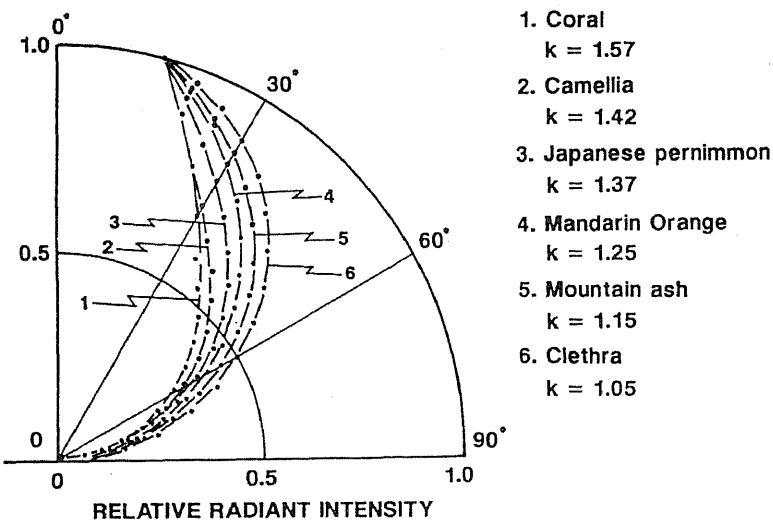


Fig. 5. Indicatrices of leaves of woody plants.

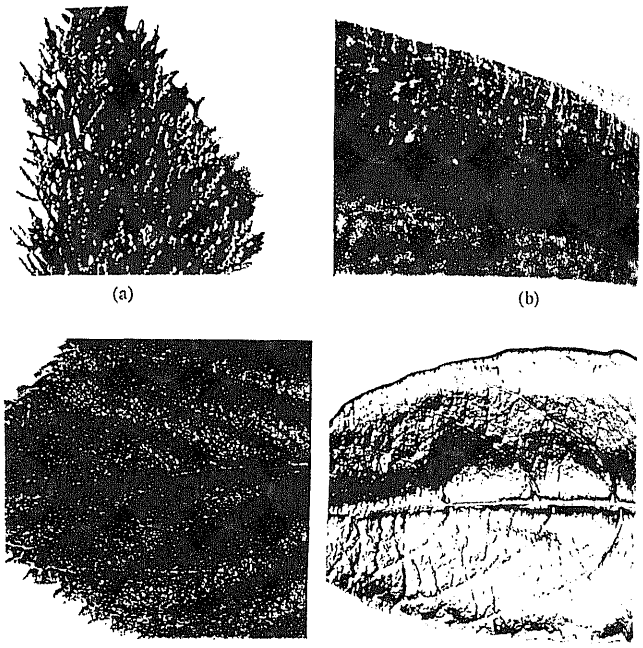


Fig. 6. Photographs showing the characteristics of leaves. (a) : **Himalaya Cedar** (k = 0.77), a needle leaf, (b) : **Snowbell** (k = 1.10), a leaf surface covered with downy hair, (c) : **Cherry** (k = 1.12), a non-specular broad leaf, (d) : **Coral** (k = 1.57), a specular leaf.

Table 2. Minnaert constants obtained from indicatrices of leaves and correlation coefficients. Leaves are classified coefficients. Leaves are classified in four groups by their Minnaert constants.

| Species (Local name) | Minnaert constant k | Correlation coefficient $R^2$ | Characteristics of leaves |
|---|---|---|---|
| **Pine** | 0.55 | 0.99 | |
| **Himalaya cedar (deodar)** | 0.77 | 0.98 | Needle leaves . |
| **Sabina Endlicher** | 0.93 | 0.90 | |
| **Platan (sycamore)** | 1.05 | 0.98 | |
| **Clethra** | 1.05 | 0.99 | The surface of a leaf is usually covered with downy hair. |
| **Ginkgo (maidenhair)** | 1.07 | 0.96 | |
| **Deciduous Camellia** | 1.07 | 0.89 | |
| **Japanese maple** | 1.09 | 0.99 | |
| **Flowering Dogwood** | 1.09 | 0.98 | |
| **Snowbell** | 1.10 | 0.99 | |
| **Cherry** | 1.12 | 0.98 | |
| **Zelkova** | 1.12 | 0.99 | The leaf has a non-specular broad leaves. |
| **Japanese hornbeam** | 1.13 | 0.98 | |
| **Mountain ash (rowan)** | 1.15 | 0.98 | |
| **Mandarin Orange (tangerine)** | 1.25 | 0.95 | |
| **Hornbeam** | 1.27 | 0.97 | |
| **Chinese hawthorn** | 1.28 | 0.97 | |
| **Oleander** | 1.28 | 0.96 | |
| **Camphor** | 1.35 | 0.90 | |
| **Japanese persimmon** | 1.37 | 0.89 | The surface of a leaf shows specular reflection. |
| **Camellia** | 1.42 | 0.89 | |
| **Spindle** | 1.46 | 0.88 | |
| **Coral** | 1.57 | 0.87 | |

for example **Platan (sycamore)**, the indicatrices present near-spherical shapes, not depending on the incident angle. The indicatrices of **Coral** with Minnaert constants of over 1.57 shown in Table 2 have the maximum in the 90° direction because the incident angle is 45° as is shown in Fig. 7.

The experimental results immediately after collection of the leaves are shown in Table 2, but the

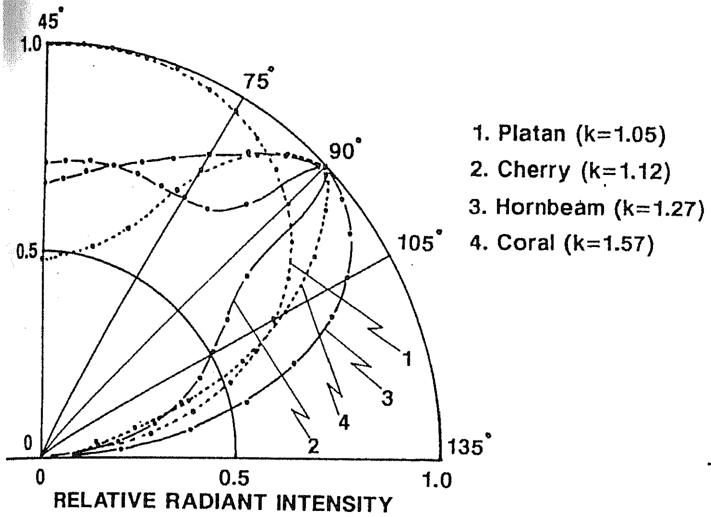


Fig. 7. Indicatrices of leaves, when the incident angle is 45 degrees to the surface of the leaf.

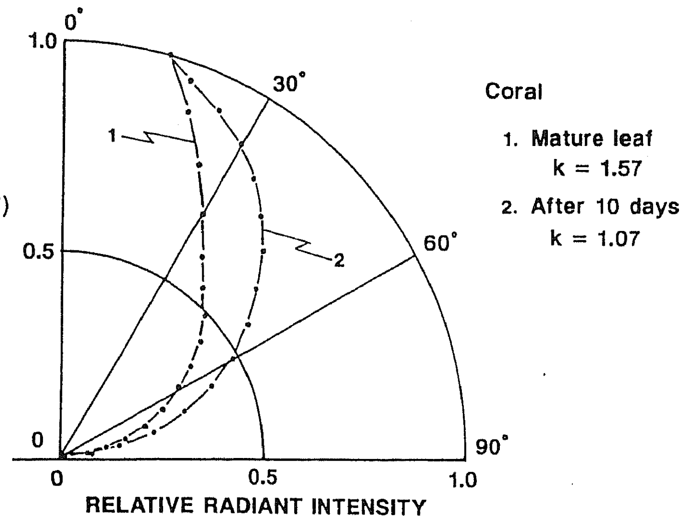


Fig. 8. Indicatrices of leaves obtained by measuring again after 10 days in the laboratory.

results which are shown in Table 3 were obtained by measuring the indicatrices again after 10 days in the laboratory. The indicatrices of the mature leaves are measured on the day of collection and 10 days after collection and the comparison is shown in Fig. 8. The leaf of **Coral** which had shown the specular reflection (1.57) in Fig. 7 did not show the specular reflection in after -10-days experiments (1.07). As shown in Table 3, Minnaert constants became smaller after ten days. This is because the leaf surfaces got rougher by evaporation of the moisture during the 10 days. Namely Minnaert constant of the leaf showing Lambertian reflection is near 1.0 and does not change even when the incident angle changes from 0° to 45° .

Table 3. Minnaert constants of leaves obtained by measuring the indicatrices again after 10 day in the laboratory.

| Species (Local name) | Minnaert constant | Minnaert constant after 10 days |
|---|---|---|
| **Ginkgo (maindenhair)** | 1.07 | 1.01 |
| **Platan (sycamore)** | 1.05 | 1.01 |
| **Cherry** | 1.12 | 0.93 |
| **Zelkova** | 1.12 | 0.68 |
| **Chinese hawthorn** | 1.28 | 1.10 |
| **Oleander** | 1.28 | 1.09 |
| **Camphor** | 1.35 | 0.86 |
| **Spindle** | 1.46 | 1.19 |
| **Coral** | 1.57 | 1.07 |

## 4. Conclusion

In general, when the reflection characteristics from the leaves of woody plants are discussed, it is assumed from the simplicity of calculation that the reflection from leaves obeys Lambertian law. However we made an experiment to obtain the indicatrices of light scattering from leaves of real woody plants. As the results from various kinds of leaves, we have found that the scattering characteristics of some of them do not obey Lambertian law. The indicatrix shows the diffuse components of reflectance. Minnaert constant does not represent the total reflectance of a leaf, but represents the degree of the reflectance intensity in angular directions. We made estimation of leaves by using Minnaert constants calculated from the indicatrices of leaves, and found that differences in the construction of the leaves gave different indicatrices.

Here we have made measurements on each piece of leaf in order to know the characteristics of respective species, but many leaves construct a layer and many layers, in turn, compose a canopy, and different results may be obtained when measured on such a scale outdoors.

## References


Allen, A. William, T. Vincent Gayle, and Arthur J. Richardson, "Plant-Canopy Irradiance Specified by the Duntley Equations", J. Opt. Soc. Am., **60**, 372-376 (1970).

Brakke, T. W. , J. A. Smith and J. M. Harnden, "Bidirectional Scattering of Light from Tree Leaves", Remote Sensing Environ., **29**, 175 - 183 (1989).

Brakke, T. W. , W. P. Wergin E. F. Erbe and J. M. Harnden, "Seasonal Variation in the Structure and Red Reflectance of Leaves from Yellow Poplar, Red Oak, and Red Maple", Remote Sensing Environ., **43**, 115 - 130 (1993).

Breece H. T. III and R. A. Hollmes , "Bidirectional Scattering Characteristics of Healthy Green Soybean and Corn Leaves in Vivo", Appl. Opt., **10**, 119 - 127 (1971).

De Hoop, A. T. , "A Reciprocity Theorem for the Electromagnetic Field Scattered by an Obstacle", Appl. Sci. Res., Section B, **8**, 135-140 (1960).

Duntley, Q. Seibert , "The Optical Properties of Diffusing Materials", J. Opt. Soc. Am., **32**, 61-70 (1942).

Kubelka, Paul , "New Contributions to the Optics of Intensely Light - Scattering Materials. Part I", J. Opt. Soc. Am., **38**, 448-457 (1948).

Kubelka, Paul , "New contributions to the Optics of Intensely Light - Scattering Materials, Part II : Nonhomogeneous Layers", J. Opt. Soc. Am., **44**, 330-335 (1954).

Minnaert, M. , "The Reciprocity Principle in Lunar Photometry", Astrophys. J., **93**, 403-410 (1941).

Suits, Gwynn H. , "The Calculation of the Directional Reflectance of a Vegetative Canopy", Remote Sensing of Environment, **2**, 117-125 (1972).

Verhoef, W. , "Light Scattering by Leaf Layers with Application to Canopy Reflectance Modeling : The SAIL Model", Remote Sensing of Environment, **16**, 125-141 (1984).