LARS Information Note 091576

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Measurements Program

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ABSTRACT

The purpose of this Information Note is to provide reference information on the performance of the LARS reflectometer for making bidirectional reflectance factor (BRF) measurements of large area (30×30 cm) samples in the 0.38 to 2.50 μm spectral region. The reflectometer facility simulates field measurement conditions for studying the effects of solar zenith angle and viewing direction on remote sensing observations of material targets. The nature of bidirectional reflectance is discussed with emphasis on accepted definitions and conventional symbols. The relationship of bidirectional reflectance factor measurements from this new reflectometer to those taken on the Beckman DK-2 integrating sphere reflectometer is explained. Results for typical sample surfaces--paints, soil, and cloth--are presented in several formats which are convenient for physical interpretation.

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LIST OF SYMBOLS

Symbol	Meaning
BRDF	bidirectional reflectance distribution function, f, sr^{-1}
BRF	bidirectional reflectance factor, $R(\theta,\phi;\theta',\phi')$
E	irradiance, $W\ m^{-2}$
f	bidirectional reflectance distribution function, BRDF, sr^{-1}
L	radiance, $W\ m^{-2}\ sr^{-1}$
R	reflectance factor
$R(\theta;\theta')$	bidirectional reflectance factor, BRF
$R_n(\theta;\theta')$	bidirectional reflectance factor normalized to near normal condition of reflectance standard
θ	polar angle or colatitude angle, °
ϕ	zenith or longitude angle, °
ω	solid angle, sr
ρ	reflectance
ρ'	bidirectional reflectance distribution function, BRDF, sr^{-1}
Φ	radiant flux, W

Subscripts

λ	spectral concentration
s	standard, barium sulfate reference

Superscripts

'	prime, refers to viewing or reflected condition
'	for R see Eq. 14

LIST OF FIGURES AND TABLES

DESCRIPTION AND EVALUATION OF A BIDIRECTIONAL REFLECTANCE FACTOR REFLECTOMETER

1. INTRODUCTION

The variation of reflectance, defined as the ratio of the reflected flux to the incident irradiation, as a function of wavelength provides the basis for classification of target scenes. The directional characteristics of the reflection process are very important to remote sensing as evidenced, for example, by the effects clouds (diffuse rather than collimated irradiation) and sun angle have on classification results.

The objective of this report is to organize the detailed technical basis for defining, measuring, and evaluating the directional reflectance characteristics of target surfaces. Since the practice and nomenclature of reflectometry is not standardized, it is easy for the uninitiated to become confused by the variety of nomenclature found in the literature. Our aim is to present a uniform nomenclature complete with symbols and definitions that are in agreement with the best practices today and in accordance with accepted international conventions.

The fundamental property providing the directional reflectance distribution characteristics of a surface is the bidirectional reflectance distribution function (BRDF); this property is difficult to measure, so more common use is made of the bidirectional reflectance factor (BRF). The reflectance measurements from field spectroradiometers and those in the laboratory by, for example, the Beckmann DK-2A Integrating Sphere

Reflectometer are quite different in the manner in which the directional characteristics are considered. For the serious experimenter, the differences are very noticeable and important as there is a great amount of important in the directional characteristics as measured by BDRF and BRF.

A purpose of this report is to develop the technical basis for comparing field measurements with measurements made by laboratory type instruments. It is important to recognize the limitations of the many simplifying assumptions that are usually made and how they can affect accuracy.

A reflectometer to obtain the BRF of typical large target samples has been designed, constructed, and the results evaluated. The system consists of a tungsten-halogen lamp with transfer optics to irradiate the sample at a one solar constant level, in a collimated directional (from normal to 45°) manner. A spectroradiometer, the Exotech Model 20C for the tests described herein, is used to sense the reflected radiance from the sample. The reflectometer, hereafter referred to as the BRF/Reflectometer, provides the remote sensing experimenter the opportunity to study the target directional characteristics in a controlled laboratory environment.

The report first deals with the principles of bidirectional reflectance measurements--definition of the related reflectance properties and how the various properties are obtained from the BRF/Reflectometer. A full description of this system is then presented in sufficient detail to appreciate its construction, features, and operation. The following section presents BRF measurements on selected targets for the purpose of illustrating the graphical forms for representing such data, discussing the typical directional characteristics (diffuseness vs. specularity) of surfaces and evaluating reflectometer performance.

2. PRINCIPLES OF BIDIRECTIONAL REFLECTANCE FACTOR MEASUREMENTS

In this section, the definitions and nomenclature relevant to bidirectional reflectance factor (BRF) measurements will be summarized. These measurements are then related to more familiar reflectance properties as measured by a laboratory integrating sphere reflectometer such as the Beckman DK-2. A section is presented on the operating principles of the BRF/Reflectometer

(1) Definitions and Nomenclature [1-5]*

Quantities

Radiant energy, Q. Energy in the form of electromagnetic wave or photons; measured in joules or ergs. Thermal radiant energy, Q, radiant energy emitted by a thermal radiator.

Radiant Flux (or power), $\Phi = dQ/dt$. Time rate of radiant energy flow; measured in erg/second or watt (W).

Radiant intensity, $I = d\Phi/d\omega$. Flux per unit solid angle from a source; measured in watts per steradian ($W\ sr^{-1}$).

Radiance, $L = d^2\Phi/d\omega dA \cos\theta$. Flux propagated in a given direction, per unit solid angle about that direction and per unit area projected normal to the direction ($dA \cos\theta$). The angle θ is measured between the direction and the normal to the unit area; measured in watts per unit area per steradian ($W\ m^{-2} sr^{-1}$).

Exitance, $M = d\Phi/dA$. Flux per unit area leaving a surface. Self exitance is the special case where the surface acts as a thermal radiator [$W\ m^{-2}$].

*The numbers in brackets designate references listed at the end of this report.

Irradiance, $E = d\Phi/dA$. Flux per unit area incident on a surface ($W\ m^{-2}$).

Properties

Reflectance, ρ. The ratio of some specified portion of the reflected flux to the incident flux.

Reflectance factor, R. The ratio of the flux reflected by a specimen under specified conditions of irradiation and viewing to that reflected by the ideal, completely reflecting, perfectly diffusing surface, identically irradiated and viewed.

Modifiers

Spectral. For a property at a given wavelength, designated by the symbols "λ" in parentheses following the symbol for the property, i.e., spectral reflectance $\rho(\lambda)$. For a quantity, spectral concentration designated by the subscript "λ", i.e., spectral radiance, $L_\lambda = d^3\Phi/d\omega dA\cos\theta d\lambda$.

Directional. Denotes an element of solid angle $d\omega$ in a single direction. The direction is completely specified by two angles, θ and ϕ; θ is the zenith angle and ϕ is the azimuthal angle as shown in Figure 1. For properties, the direction indicating symbols θ and ϕ are enclosed in parentheses following the symbols for the property as in $\rho(\theta,\phi;\theta',\phi')$; the symbols indicating the incident direction given first followed by a semicolon, then the prime symbols indicating the direction of the reflected rays. The modifier <u>normal</u> is used to identify the special case where the direction is normal or nearly normal to the surface.

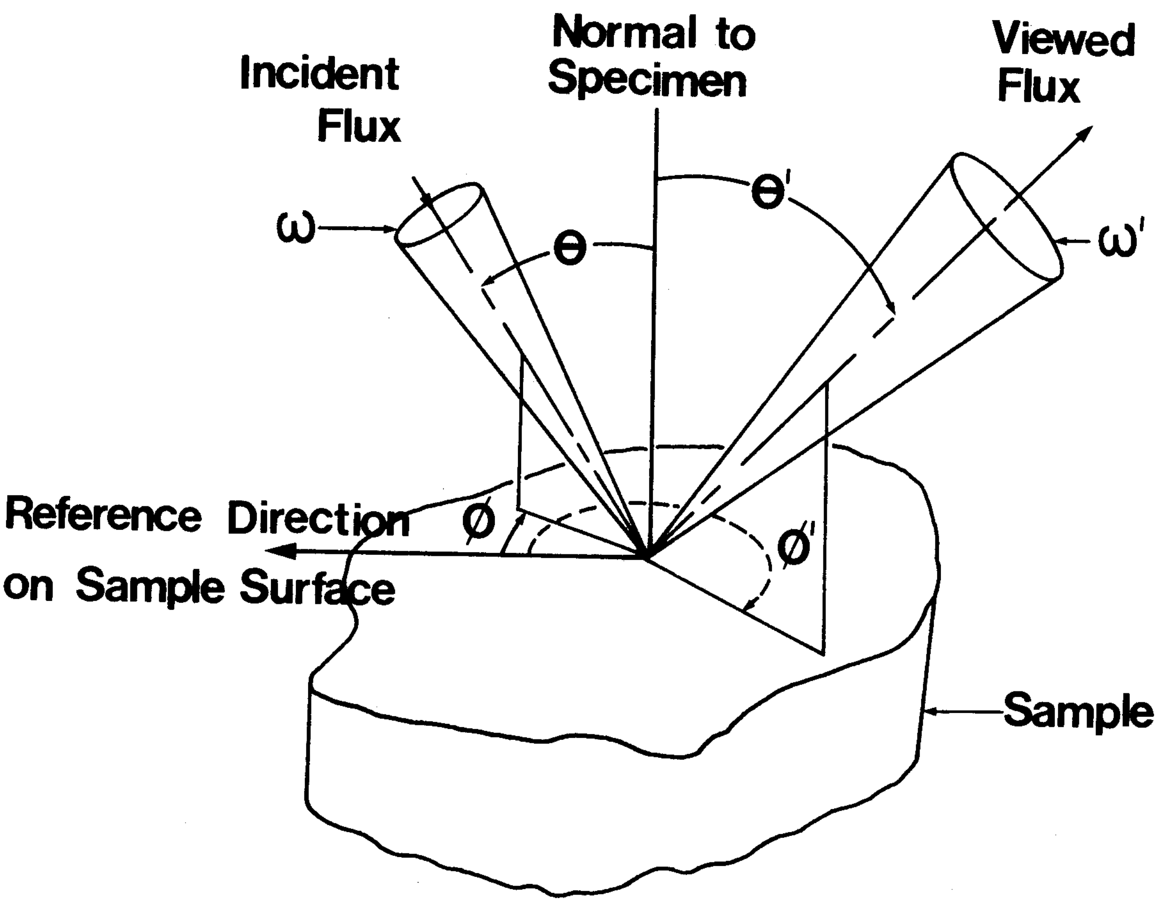

Figure 1. Geometric Parameters Describing Reflection from a Surface: θ = Zenith Angle, ϕ = Azimuthal Angle; ω = Beam Solid Angle, sr. A prime on a symbol refers to Viewing (or Reflected) Conditions.

Conical. Over a finite solid angle smaller than a hemisphere. The direction of the solid angle is indicated by θ, ϕ and the magnitude by the symbol ω [assuming a right-circular cone]. Primed symbols are used to indicate the reflected beams.

Hemisphere. Over a complete hemisphere designated by the symbol 2π replacing the symbols θ, ϕ, ω in parentheses following the symbol for the property or quantity.

Specular. In the direction of mirror reflection.

Diffuse. Applied to a reflector (or transmitter) reflecting (or transmitting) in all directions over a hemisphere. Applied to incident radiant energy, incident from all angles over a hemisphere.

Perfectly diffuse. With equal radiance in all directions from a surface. Also referred to as a Lambertian Reflector.*

(2) Bidirectional Reflectance Distribution Function and Related Properties

The most fundamental and widely accepted property describing the reflection characteristics of a surface is the bidirectional reflectance distribution function (BRDF) denoted by the symbol f, defined as**

$$f(\theta,\phi;\theta',\phi') \equiv \frac{dL'(\theta',\phi')}{dE(\theta,\phi)} \qquad [sr^{-1}] \qquad [1]$$

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*The radiance of a uniformly illuminated Lambertian surface of infinite extent is constant for any viewing angle (θ'). If a uniformly illuminated Lambertian surface is small enough so as not to fill the field of view of an observing instrument, the radiance measured by the instrument will be proportional to the cosine of the viewing angle.

**For simplicity the solid angles ω and ω' are explicitly stated only in subsequent expressions where their magnitudes are a factor in the reflectance property. It is assumed that ω or ω' are small enough such that the property or quantity does not vary appreciably over these angles.

That is, BRDF is the quotient dL'/dE, with units sr^{-1} and is a function of the incident and reflected directions expressed by $\theta,\theta';\phi,\phi'$. Occasionally $f(\theta,\phi;\theta',\phi')$ is denoted as $\rho'(\theta,\phi;\theta',\phi')$. The term dL' ($W\ m^{-2}\ sr^{-1}$) is the reflected radiance in the direction θ',ϕ' produced by the incident irradiance dE ($W\ m^{-2}$) of a well collimated beam from the direction θ,ϕ and may be expressed as

$$dE(\theta,\phi) = L(\theta,\phi)\cdot\cos\theta d\omega \qquad [W\ m^{-2}] \qquad [2]$$

where $L(\theta,\phi)$ is the incident radiance from the direction θ,ϕ through the solid angle $d\omega$ expressed in spherical coordinates as

$$d\omega = \sin\theta d\theta d\phi \qquad [sr] \qquad [3]$$

The measurement of a complete BRDF is obviously quite extensive. Furthermore, the equipment required to obtain all the terms in Equation [1] is complex because, in general, accurate measurement of the irradiance at the surface of the sample and of the reflected radiance of the sample is difficult.

The following reflectance concepts may be related through the BDRF. The bidirectional reflectance is expressed as

$$d\rho(\theta,\phi;\theta',\phi') = \frac{dL'(\theta',\phi')\cos\theta' d\omega'}{L(\theta,\phi)\cos\theta d\omega} = f(\theta,\phi;\theta',\phi')\cos\theta' d\omega' \qquad [4]$$

The term $d\rho$ is not only a measure of the directional reflecting properties of the surface but also directly proportional to the size of the projected solid angle of reflection, $\cos\theta' d\omega'$.

This expression does not yield a unique property of the sample but is dependent upon the instrumentation configuration used to make the measurement. This can most easily be appreciated by the following consideration: The incident flux is fixed by source characteristics and the solid angle of irradiation $d\omega$. The flux reflected in any direction over the hemisphere that will be sensed by the instrument is determined by the value of $d\omega'$, the solid angle of the reflected radiance, which may be quite different from $d\omega$. This is an inconvenience and a source of confusion to the user of such measurements.

The previously defined reflectance factor is a property which is relatively easy to measure because comparatively simple equipment can be used. Integrating sphere reflectometers such as the Beckman DK-2 instrument are frequently used to make reflectance factor measurements in the visible and near infrared regions of the spectrum. Although the ideal, completely diffusing surface does not exist, several materials such as smoked magnesium oxide, magnesium carbonate, and barium sulfate are very good approximations in the aforementioned spectral range, 0.3 to 2.5 μm. For reflectance measurements beyond 2.5 μm, instrumentation utilizing mirror collecting optics have been successfully developed but as yet are not widely used.

Reciprocity Relations

The fundamental expression from which various types of reflectances and reflectance factors may be related is the Helmholz reciprocity theorem:*

$$f(\theta,\phi;\theta',\phi') = f(\theta',\phi';\theta,\phi) \quad [5]$$

Following the geometry of Figure 1 where subscripts indicate specific values of the parameters θ, ϕ, and ω and with the restriction that the radiance does not vary over the solid angle of incidence in either case,

*Several proofs of this theorem are identified in Reference [6].

Equation [5] can be shown to yield

$$\frac{\rho(\theta_1,\phi_1,\omega_1;\theta_2,\phi_2,\omega_2)}{\cos\theta_2\omega_2} = \frac{\rho(\theta_2,\phi_2,\omega_2;\theta_1,\phi_1,\omega_1)}{\cos\theta_1\omega_1} \quad [6]$$

where ρ is the bidirectional reflectance measured by the small but finite solid angles ω_1 or ω_2. By use of Equation [6] the following relations* can be developed:

Reciprocity of Reflectance Factors:

$$R(2\pi;\theta_1,\omega_1) = R(\theta_1,\omega_1;2\pi) \quad [7]$$

Reflectance Factor Relations:

$$\rho(2\pi;2\pi) = R(2\pi;2\pi) \quad [8]$$

$$\rho(\theta,\omega;2\pi) = R(\theta,\omega;2\pi) \quad [9]$$

where θ and ω are the same for ρ and R.

Bidirectional Relations:

$$R(\theta_1,\omega_1;\theta_2,\omega_2) = R(\theta_2,\omega_2;\theta_1,\omega_1) \quad [10]$$

$$\rho(\theta,\omega;\theta',\omega') = \frac{\omega'\cos\theta'}{\pi} R(\theta,\omega;\theta',\omega') \quad [11]$$

Bidirectional Reflectance Factor

The concept of the reflectance factor when applied to BRDF provides a simplification for measurement and interpretation of the results. It can be shown that the BRDF of an "ideal, completely reflecting perfectly diffusing surface" is $1/\pi$ sr^{-1} [6]. This follows from the fact that the reflected radiance must be uniform over the hemisphere and would hence be a factor $1/\pi$ of the irradiance. That is, for this perfect diffuser:

$$f(\theta,\phi,\theta',\phi') = \frac{1}{\pi} \qquad [sr^{-1}] \quad [12]$$

*For simplicity the azimuthal angles ϕ and ϕ' have not been carried through.

Consider now what will result if we determine the ratio of the reflected radiance, the numerator of the BRDF, of a sample to the reflected radiance of the perfect diffuser. It follows then that

$$R(\theta,\phi;\theta',\phi') = \pi f(\theta,\phi;\theta',\phi') \qquad [13]$$

which relates the bidirectional reflectance factor, BRF, to the bidirectional reflectance distribution function, BRDF, for any surface.

(3) Beckmann DK-2 Reflectance Measurements

The Beckmann DK-2 with integrating sphere attachment provides normal-hemispherical (spectral) reflectance factors, $R(6°;2\pi)$, assuming the reference standard to be perfect.* Since this is not generally the case, the measurements need to be corrected by the known spectral reflectance of the standard $\rho_s(6°;2\pi)$; that is,

$$R(6°;2\pi) = \rho_s(6°;2\pi)R'(6°;2\pi) \qquad [14]$$

where R' is the actual measured reflectance factor using a nonperfect reference standard of reflectance ρ_s. Typical values of ρ_s for smoked magnesium oxide and barium sulfate are presented in Appendix A.

(4) Operating Principles of the BRF Reflectometer

The geometric parameters describing the manner in which the sample target of the BRF/Reflectometer is irradiated and viewed is illustrated in Figure 2. Two essential features of the analytical model of this

*Normal in this instance means "nearly normal" or approximately 6°. Reflectances of magnesium oxide and barium sulfate are recorded in the Appendix A. As a matter of convenience in reporting measurements in the literature, it is sufficient to report reflectance factor data relative to freshly smoked magnesium oxide, for example. The confusion and/or errors associated with such reporting are minimal.

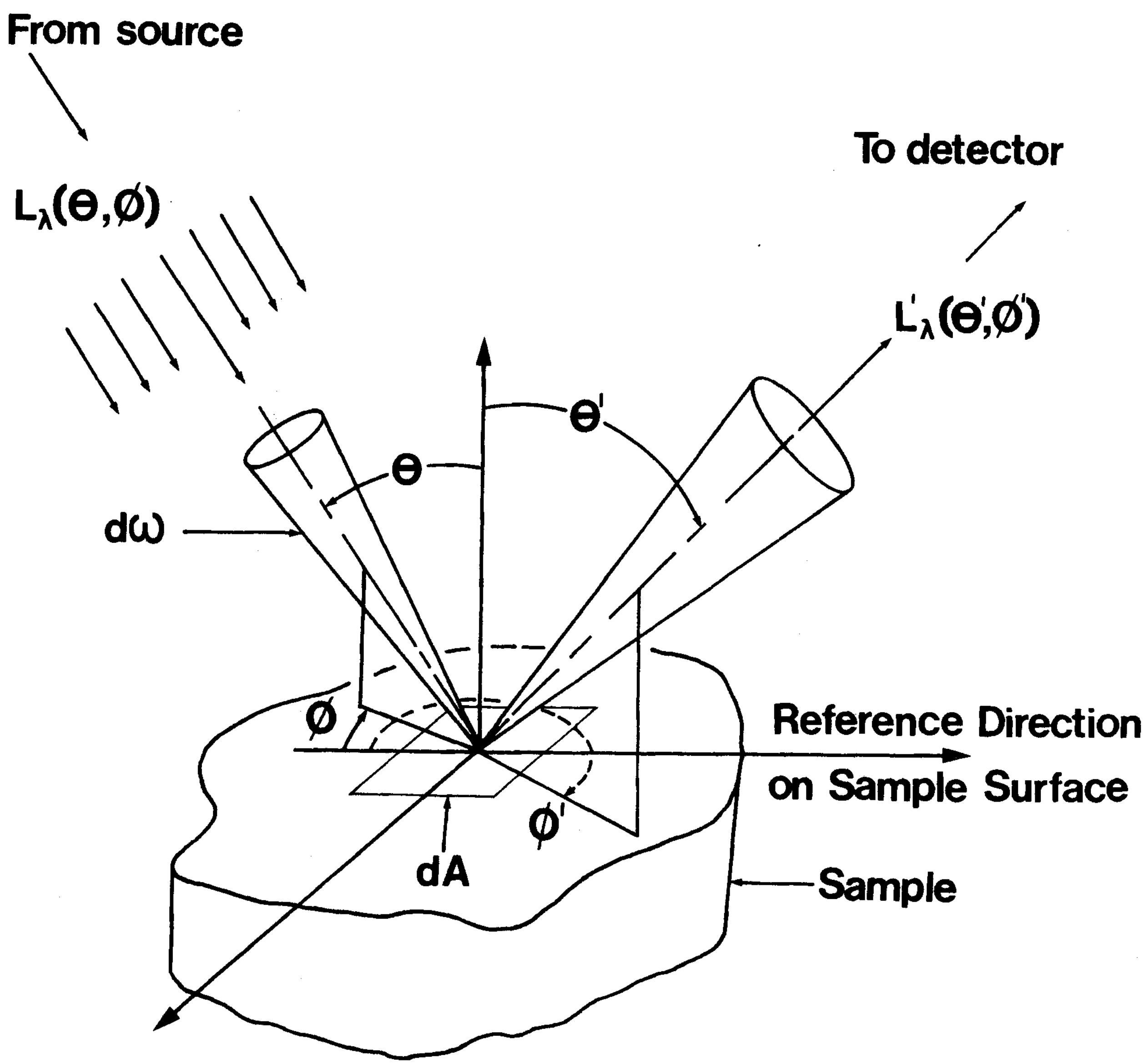

Figure 2. Geometric Parameters Describing Reflection from an Elemental Area, dA, of the Sample

measurement method are that the target area is uniformly irradiated and that the incident radiance is likewise uniform and highly collimated. It should be clear as the model is developed how these two features simplify the treatment. Deviations from the model assumptions can be observed but are determined to be negligible as will be later shown.

The radiant flux incident* upon the differential element dA of the target sample is

$$d^2\Phi = L(\theta,\phi)\cos\theta dA d\omega \qquad [W] \qquad [15]$$

where $L(\theta,\phi)$ is the incident radiance from a system consisting of a source and transfer optics. The irradiance on the target area, dE ($W\ m^{-2}$), is expressed as

$$dE(\theta,\phi) = \frac{d\Phi(\theta,\phi)}{dA} = L(\theta,\phi)\cos\theta d\omega \qquad [W\ m^{-2}] \qquad [16]$$

From the definition of the bidirectional reflectance distribution function, BRDF, Equation [2], the reflected radiance in the direction θ',ϕ' is

$$dL'(\theta',\phi') = f(\theta,\phi;\theta',\phi')\cdot dE(\theta,\phi) \qquad [W\ m^{-2}sr^{-1}] \qquad [17]$$

The flux reaching the detector (or spectroradiometer optics in this instance), represented by the symbol Φ_d, can be written as

$$\Phi_d = \int_{FOV} L'(\theta',\phi')\cos\theta' dA d\omega' \qquad [W] \qquad [18]$$

where the integration is over the field of view (FOV) of the spectroradiometer indicated by the primed symbols. Using Equations [17] and [16]

*For convenience, the spectral subscript λ will not be used but the model applies to the case of spectral radiance.

for the incident radiance and target irradiance, respectively, gives the flux reaching the detector in terms of the BRDF

$$\Phi_d = \int_{FOV} f(\theta,\phi;\theta',\phi')\cdot L(\theta,\phi)\cos\theta d\omega\cdot\cos\theta' dA d\omega' \qquad [W] \qquad [19]$$

Carefully note that the integration is performed over the FOV or primed symbols.

To reduce this integral to a more manageable form, the assumptions are made that the BRDF varies negligibly with θ',ϕ' and with dA within the limits of the FOV. In the case of the Exotech Model 20 Spectroradiometer the field of view is quite small: 3/4° half plane angle and 3.2 cm dia target area. Hence, Equation [19] reduces to:

$$\Phi_d = f(\theta,\phi;\theta',\phi')\cdot L(\theta,\phi)\cos\theta d\omega\cdot\cos\theta'\Delta A\Delta\omega' \qquad [W] \qquad [20]$$

where $\Delta A\Delta\omega'$ represents the FOV limits.

To simplify the measurement procedure, the comparative approach is adopted using a reference standard which is an approximation to an ideal, totally reflecting, perfectly diffuse reflector. Since the detector signal is proportional to the radiant flux incident upon it, the ratio of the detector signals for a specimen to that of the standard denoted by the subscript s, is:

$$\frac{\Phi_d}{\Phi_{d,s}} = \pi f(\theta,\phi;\theta',\phi') \qquad [21]$$

since the BRDF of the reference standard is $1/\pi$ as determined from Equation [12]. Furthermore, we know from Equation [13] that the detector signal ratios can be expressed in terms of the BRF.

$$\frac{\Phi_d}{\Phi_{d,s}} = R(\theta,\phi;\theta',\phi') \qquad [22]$$

(5) Comparison of the Beckmann DK-2 and BRF/Reflectometer Measurements

The relationship between the properties measured by the Beckmann DK-2 Reflectometer and the BRF/Reflectometer can be developed as follows: The reflected radiance from the sample using Equation [2] and [3] is

$$dL'(\theta',\phi') = f(\theta,\phi;\theta',\phi')L(\theta,\phi)\cos\theta d\omega \quad [\mathrm{W\ m^{-2}sr^{-1}}] \qquad [23]$$

where θ, ϕ, and ω refer to irradiance condition. The total reflected flux, Φ', becomes

$$\Phi' = \int_{\Omega} dL'(\theta',\phi')dA\cos\theta' d\omega' \quad [\mathrm{W}] \qquad [24]$$

and using Equation [3] for the solid angle $d\omega$ the result is

$$\Phi' = \int_0^{2\pi}\int_0^{\pi/2} dL'(\theta',\phi')\, dA\cos\theta'\sin\theta' d\theta' d\phi' \quad [\mathrm{W}] \qquad [25]$$

From the definition of the directional-hemispherical reflectance $\rho(\theta,\phi;2\pi)$ we can write

$$\rho(\theta,\phi;2\pi) = \frac{\Phi'}{\Phi} = \frac{\Phi'}{L(\theta,\phi)\cos\theta dA d\omega} \qquad [26]$$

Substituting the expression for Φ' from Equation [25] into Equation [26], we obtain after some manipulation

$$\rho(\theta,\phi;2\pi) = \int_0^{2\pi}\int_0^{\pi/2} f(\theta,\phi;\theta',\phi')\cos\theta'\sin\theta' d\theta' d\phi' \qquad [27]$$

This relationship can also be written in the form of BRF values as

$$R(\theta,\phi;2\pi) = \int_0^{2\pi}\int_0^{\pi/2} \frac{1}{\pi} R(\theta,\phi;\theta',\phi')\cos\theta'\sin\theta' d\theta' d\phi' \qquad [28]$$

A simple test on this relationship follows when the sample is perfectly diffuse. In this instance, the reflected radiance is independent of direction and hence $f(\theta,\phi;\theta',\phi')$ for any θ,ϕ value is independent of θ',ϕ' and then the relation reduces to this form for the perfect diffuser: $\rho(\theta,\phi;2\pi) = \pi f(\theta,\phi;\theta',\phi')$. The Equation [27] expresses the directional-hemispherical reflectance $\rho(\theta,\phi;2\pi)$ as a function of the BRDF, $f(\theta,\phi;\theta',\phi')$. The former property is equal to the reflectance factor, $R(\theta,\phi;2\pi)$--the value measured by the Beckmann Reflectometer*--according to Equation [9]. The latter property can be expressed in terms of the BRF, $R(\theta,\phi;\theta',\phi')$--the value measured by the BRF/Reflectometer--according to Equation [13]. Hence, to obtain the property equivalent to the Beckmann Reflectometer, then Equation [28] becomes

$$R(6°;2\pi) = \int_0^{2\pi}\int_0^{\pi/2} \frac{1}{\pi} R(6°;\theta',\phi')\cos\theta'\sin\theta' d\theta' d\phi' \qquad [29]$$

where the BRF is written to include the azimuthal coordinate even though in general this dependency is negligible or ignored. Note that the integral is performed over the range of the viewing angle parameters, θ',ϕ' The BRF/Reflectometer measurement on samples, however, is usually reported for the conditions of variable incident (θ) and fixed normal viewing, $\theta' = 0$; that is, available data is for $R(\theta;0°)$ with θ = 5 to 60°. Using the

*The sample plates of the Beckmann DK-2 Integrating Sphere Reflectometer are in the "total" position.

reciprocity relation, Equation [10],

$$R(0°;\theta',\phi') = R(\theta',\phi';0°) \qquad [30]$$

where now the integral of Equation [29] can be completed using the measured BRF values as indicated by the right-hand side of this relation. These procedures are used in the intercomparison of the green color panel measurements reported in Table 1.

3. DESCRIPTION OF THE BIDIRECTIONAL REFLECTANCE FACTOR REFLECTOMETER

(1) General Features

A schematic illustrating the measurement method and identifying the key features of the bidirectional reflectance factor system is shown in Figure 3. The sensing head of the Exotech Model 20 Spectroradiometer is mounted in a vertical fixed positon approximately 2.4 m above the sample stage. The sample stage is spindle mounted allowing the sample to be rotated about a centerline passing through the coincidence point of the irradiation and viewing directions. The limits of rotation of the sample stage are fixed by a pin-hole arrangement allowing the following pre-set angles as measured from the vertical: ±0, 22.5°, 33.7°, and 45°. The sample stage was designed to accommodate samples of differing thicknesses and through the use of adjusting screws, the sample surface can be brought to the proper height, that is, to be in the viewing plane. The sample limitations are 30 cm major dimension, 5 cm maximum thicknesses, and 11 kg weight.

The source and its transfer optics, subsequently described in detail, are mounted on an arm such that the center of rotation passes through the sample surface. This arm can be rotated ±60° measured from the vertical, the limits being set by interference with the floor. The arm can be positioned at any setting by means of a collar/slide arrangement and the position indicated by a protractor scale with a least count of 2°. The arm, when in the near normal position, blocks the Exotech viewing path over the range ±5°. A description of the Exotech Spectroradiometer is contained in Reference 7.

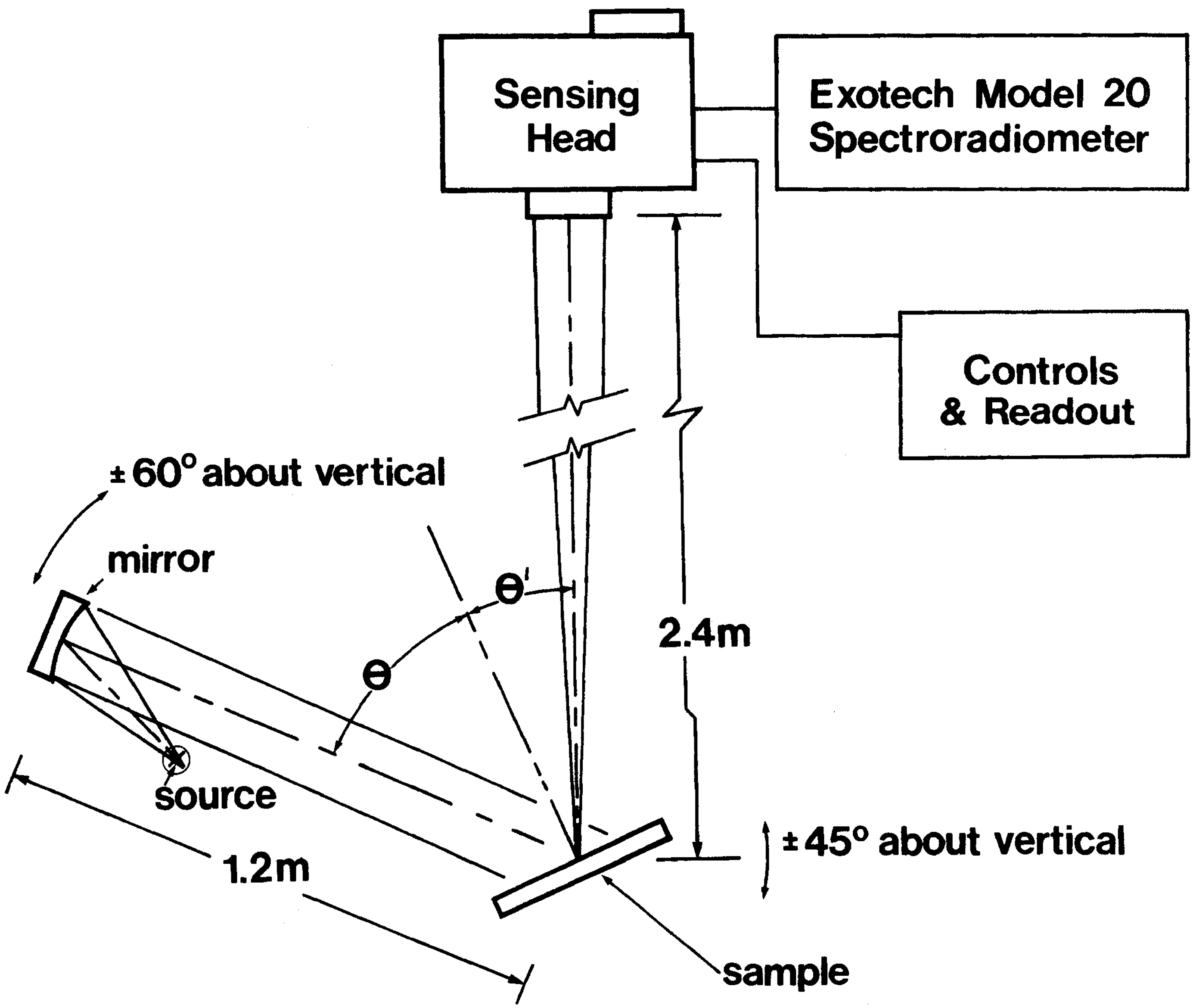

Figure 3. Schematic of the BRF/Reflectometer

(2) Source and Transfer Optics

The source is a 1000 watt tungsten iodine coiled filament lamp, GE DXW, mounted in a light, tight air-cooled housing. An off-axis (6°) paraboloidal mirror of diameter 15 cm and focal length 440 mm, views the source and transfers a highly collimated beam to the sample-viewing plane. During the preliminary evaluation of the reflectometer, a lower cost spherical mirror of 15 cm diameter and focal length 450 mm, was operated approximately 4.5° off axis to irradiate the sample plane. Aberations for this slight off-axis condition were modest and good collimation, estimated at less than 3°, was achieved. Mapping of the flux on the sample plane using the spherical mirror is presented in Figure 5. Also on this plot are shown the viewing areas for the Exotech Spectroradiometer. The skewed distribution of constant irradiance lines is a consequence of the spherical mirror off-axis operation. Across the Exotech Spectroradiometer FOV, the irradiance level change is approximately 4% which is deemed satisfactory for acquiring the data desired by this system. With the paraboloidal mirror, the degree of collimation and irradiance nonuniformity at the sample will decrease appreciably; at the time of this work, the mirror had not been mounted and evaluated.

The source is driven by a Sorensen 150-10A DC power supply with ±0.2% current regulation.* After proper aging of the lamp and temperature stabilization of the housing, spectral radiance stabilities of ±1/2% could be routinely achieved. With air cooling, the finned lamp housing operated at 70°C and contact by the operator should be avoided. The primary purpose

*From 0-95% load voltage change and ±10% line voltage change combined.

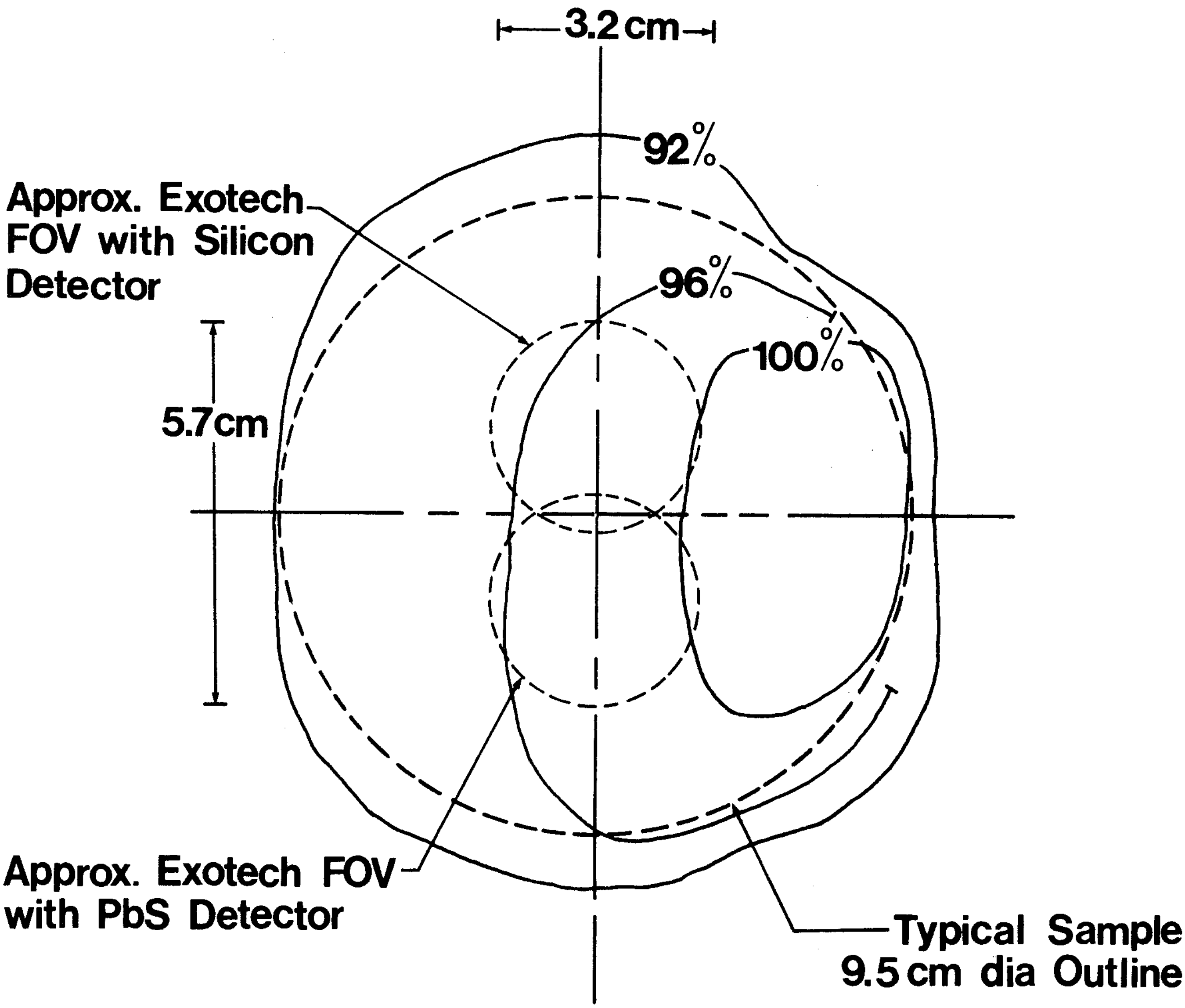

Figure 4. Equal Irradiance Contours on Sample Plane in Relation to Exotech Spectroradiometer FOV. Approximate target irradiance, 370 W m^{-2}.

of the lamp housing is to minimize the amount of stray light reaching the spectroradiometer. If the lamp is operated without a suitable housing, light reflected from room walls or parts of the reflectometer can introduce sizable systematic errors.

4. EVALUATION OF BRF MEASUREMENTS

(1) Description of Samples

A series of samples were selected for performance evaluation of the BRF/Reflectometer. The choices were based upon their characteristics as typical of the types of samples to be studied by remote sensing experimenters or would serve to test some features of the reflectometer.

The samples are identified as follows and a brief description of their preparation is given:

Barium sulfate--(Eastman 6091 white reflectance standard) 12.7 cm diameter × 1 cm. Pressed with matte glass surface in drill press to a density of slightly less than 2 grams/cm^3.

White paint--(3M Nextal White Spray Can) lightly roughened aluminum surface cleaned with acetone. Sprayed several light coats to obtain a uniform matte surface.

Green color panel--canvas folded; developed by Meade Technology for use as calibration ground truth panels.

Roughened aluminum--heavily roughened with several grades of coarse sandpaper.

Black 3M paint--(3M Nextal Black Spray Can) lightly roughened aluminum surface. Cleaned with acetone. Sprayed several light coats.

Soil sample--air dried, powdery soil with some small lumps poured into sample holder shaken down to make level surface. While no particular attempt was made to characterize this sample, it was typical of the air dry samples of interest to soil scientists.

(2) Measurement Procedures

Preliminary checks were made to establish that the angle of observation was 0° with respect to sample normal when the sample was level. The field of view of the sensor was established for the visible and for the near infrared and the samples were positioned on the optical centerline.

With the cooling fan operating, the lamp was brought to full power (1000 watts) in small steps to avoid thermal shock to the lamp and housing. Upon reaching approximately 8.3 amperes the supply was operated in the current limited mode. Following this a 20 minute warmup period was allowed.

A system stability check was accomplished with a white painted target. The circular variable filters were stopped at specific wavelengths and the system outputs were monitored with a digital voltmeter. System stability and repeatability (that is, including sample and source angular repeatibility) was better than ±3% for a measurement period of ten minutes.

Measurement for each angular arrangement was accomplished obtaining the spectral response of the instrument to the barium sulfate in the level position and in the angular position. Then the subject samples were positioned in the angular position. This procedure allowed for the investigation of the directional properties of the barium sulfate sample as well as the bidirectional reflectance factors of the samples.

(3) Presentation and Discussion of Results

The results of observations taken on the six samples for four wavelengths 0.54, 0.70, 1.21, and 1.55 μm are recorded in Appendix B. Reflectance factor measurements over the spectral range 0.4 to 2.4 μm are possible, but treatment of only four specific wavelengths is deemed adequate for analysis purposes. The calculated values appearing in the table of Appendix B are:

$R(\theta;\theta')$--BRF, bidirectional reflectance factor, as defined by Equations [13] and [22]; the barium sulfate sample is considered to be the "perfectly reflecting and perfectly diffuse" reference standard; $f(\theta;\theta')/f_s(\theta;\theta')$ where the subscript s denotes the barium sulfate.

$R_n(\theta;\theta')$--BRF, bidirectional reflectance factor, normalized to the near-normal condition of the reference standard, barium sulfate; $f(\theta;\theta')/f_s(5°;0°)$. The property $R_n(\theta;\theta')$ has particular utility in evaluating performance and also has been used to some extent in the literature.

The BRF measurements on the six test samples at 0.54 μm are presented on polar coordinates in Figure 5 for the condition of normal viewing. The polar coordinate method of presentation is the most traditional manner of displaying the BRF of a surface to illustrate its degree of diffuseness; the perfect diffuser has a BRF independent of angle and hence appears as a circle. The left-hand portion of this polar plot Figure 5 is the property $R_n(\theta;\theta')$ for the barium sulfate sample, the reference standard. By definition the value at (5°;0°) will be unity and if the barium sulfate were "perfect" and the reflectometer operating without error, all $R_n(\theta;\theta')$ values would likewise be unity.

At the wavelength 0.54 μm, as shown in the Figure 5, the values of $R_n(\theta;0°)$ for the barium sulfate are within 3% of exhibiting perfect diffuseness over the range θ = 0 to 60°, the direction of irradiation.
The $R_n(\theta;0°)$ values for the wavelengths 0.70, 1.21, and 1.55 μm (tabulated in Appendix B) are within a 4% limit excepting for the R(60°;0°) value at 1.55 μm where the departure from diffuseness is closer to 6%. Figure 6 represents $R_n(\theta;0°)$ for the four selected wavelengths plotted on

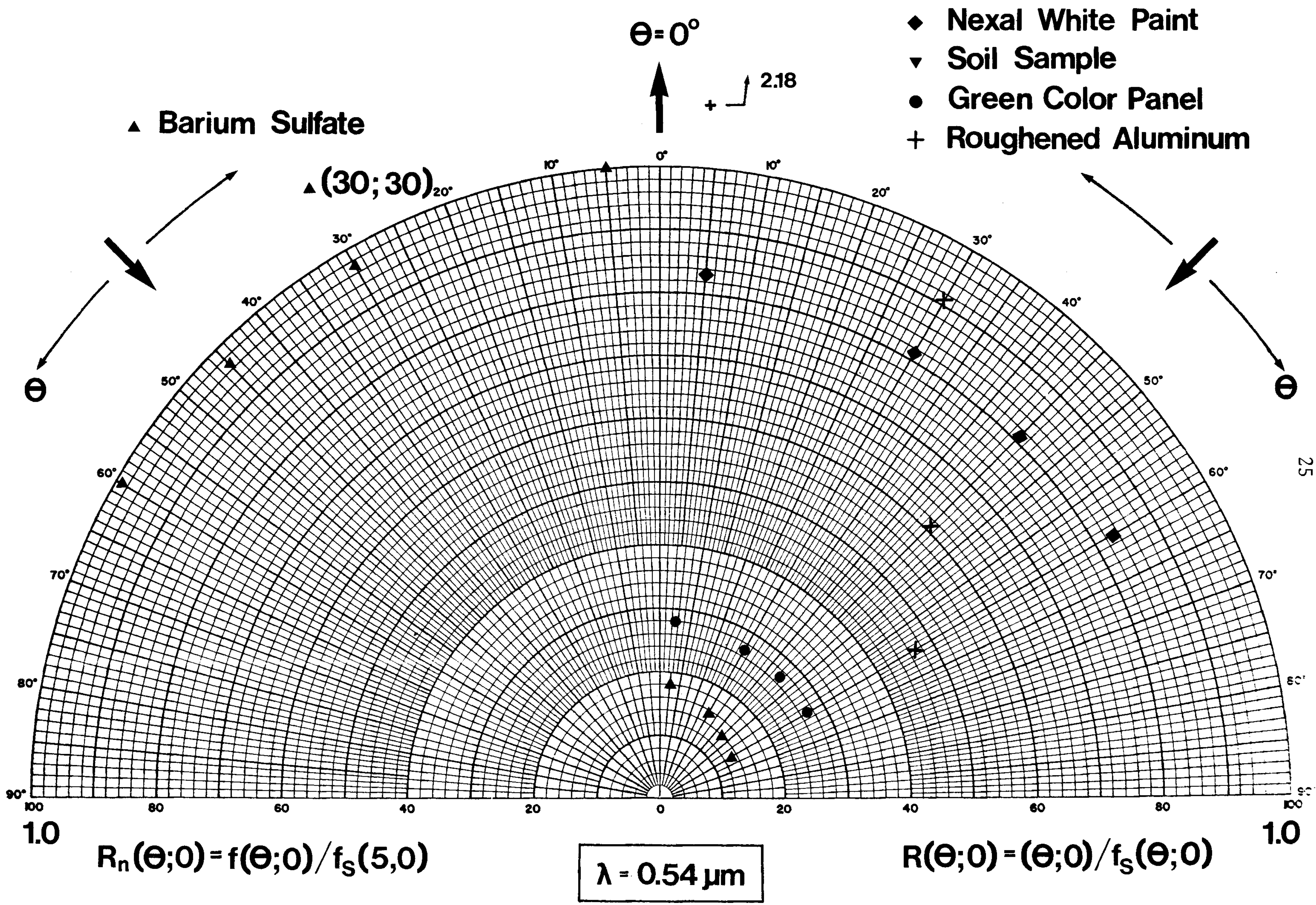

Figure 5. Representation of BRF Measurements for the Six Samples at 0.54 μm--Polar Coordinates.

Cartesian coordinates as a function of viewing angle θ'. In this type of representation, the perfect diffuser would be a horizontal line and the departure from diffuseness can also be easily seen.

Particularly interesting on this Figure 5 for the barium sulfate measurements is the one point $R_n(30°;30°)$ which is taken under the condition of viewing in the specular reflection direction. Under this condition, if the surface has any gloss, $R_n(\theta_0;\theta_0')$ will be greater than unity, while if the material is a backscatterer, $R_n(\theta_0;\theta_0')$ will be less than unity. For the four wavelengths studied, the following results were found:

λ (μm)	0.54	0.70	1.21	1.55
$R_n(30°;30°)$	1.114	0.893	0.905	0.875

In general, barium sulfate when properly prepared is highly diffuse with noticeable deviations (say, 1-2%) occurring when $\theta' > 60°$, [8]. The BRF values $R_n(\theta;\theta')$ taken on the barium sulfate reference as represented in Figures 5 and 6 are quite satisfactory. Except for the specular conditions (30°;30°) and the apparent nondiffuseness for the (0°;60°) condition at 1.55 μm, the performance of the reflectometer and/or preparation of the barium sulfate reference are acceptable.

On the right-hand portion of the Figure 5, the BRF, $R(\theta;0°)$ of the five test samples for normal viewing is shown on polar coordinates. The advantage of representation of the BRF on polar coordinates is the ease with which deviation from perfect diffuse or Lambertian behavior can be seen. The white Nextal paint appears to be a rather good diffuser, for at least normal incidence conditions. Likewise, the green color panel appears quite diffuse. By comparison, the soil sample appears to be a

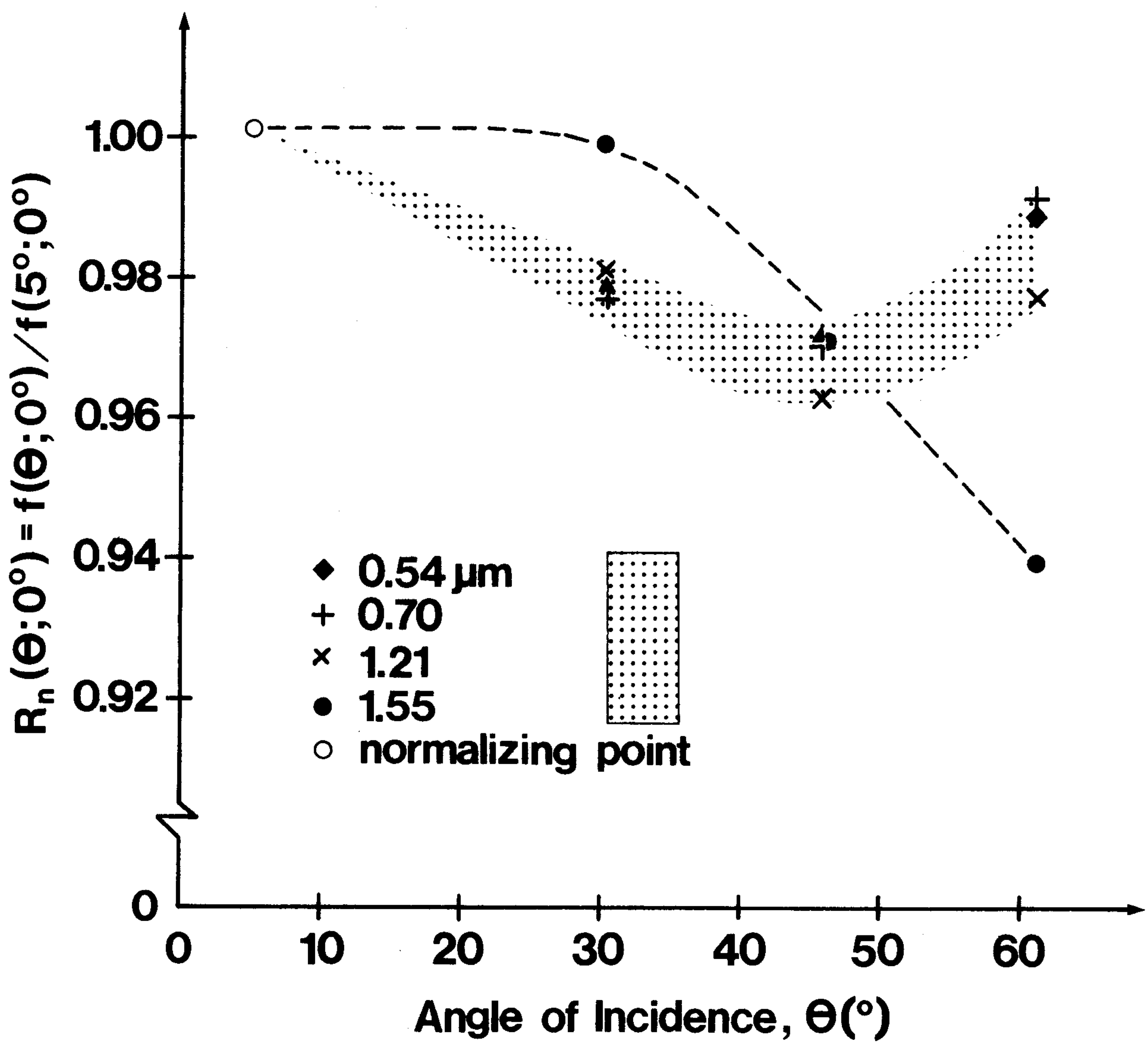

Figure 6. Normalized Bidirectional Reflectance Factor $R_n(\theta;0°)$ for Normal Viewing Conditions as a Function of Angle of Incidence, θ, for the Barium Sulfate Reference Sample.

poor diffuser. The roughened aluminum sample displays a prominent specular reflection component which is typical of most metallic roughened surfaces in the visible spectrum. Only under the proper combination of wavelength and roughness does a metal approach diffuse reflection characteristics.

On Figure 7, the normalized BRF, $R_n(\theta;0°)$, for all six samples are presented in Cartesian coordinates for the wavelength $\lambda = 0.54$ µm. A perfect diffuser would be represented by a horizontal straight line. Deviations from perfect diffuseness are easily seen as was the case with the polar coordinate representation. However, in Cartesian coordinates, it is easier to discern scatter of the measurements. Notice the scatter for the Nextal black paint which quite obviously is the result of very low reflected flux signal levels. For all the other five samples, scatter of the measured values of $R_n(\theta;0°)$ are within ±0.02 reflectance units based upon a straight line curve fit.

Figure 8 provides a representation of $R_n(\theta;0°)$ for the soil sample and green color panel at four wavelengths--0.54, 0.70, 1.21, and 1.55 µm. For the soil sample, the BRF at the three longer wavelengths is spectrally flat within 0.03 reflectance units and the data is represented as a band. Since the magnitude of the BRF will vary slightly from sample to sample (presumably of the same texture, etc.), it is interesting to note how monotonous the BRF values are as a function of wavelength.

The green color panel data for four wavelengths is represented in Figure 8 as $R_n(\theta;0°)$ and in Figure 9 as $R(\theta;0°)$ with an expanded ordinate. In this Figure 9, there is a noticeable increase in the curvature of the BRF for higher angles of incidence, θ, as the value of the BRF increases. This effect can be explained by the classical electromagnetic wave theory

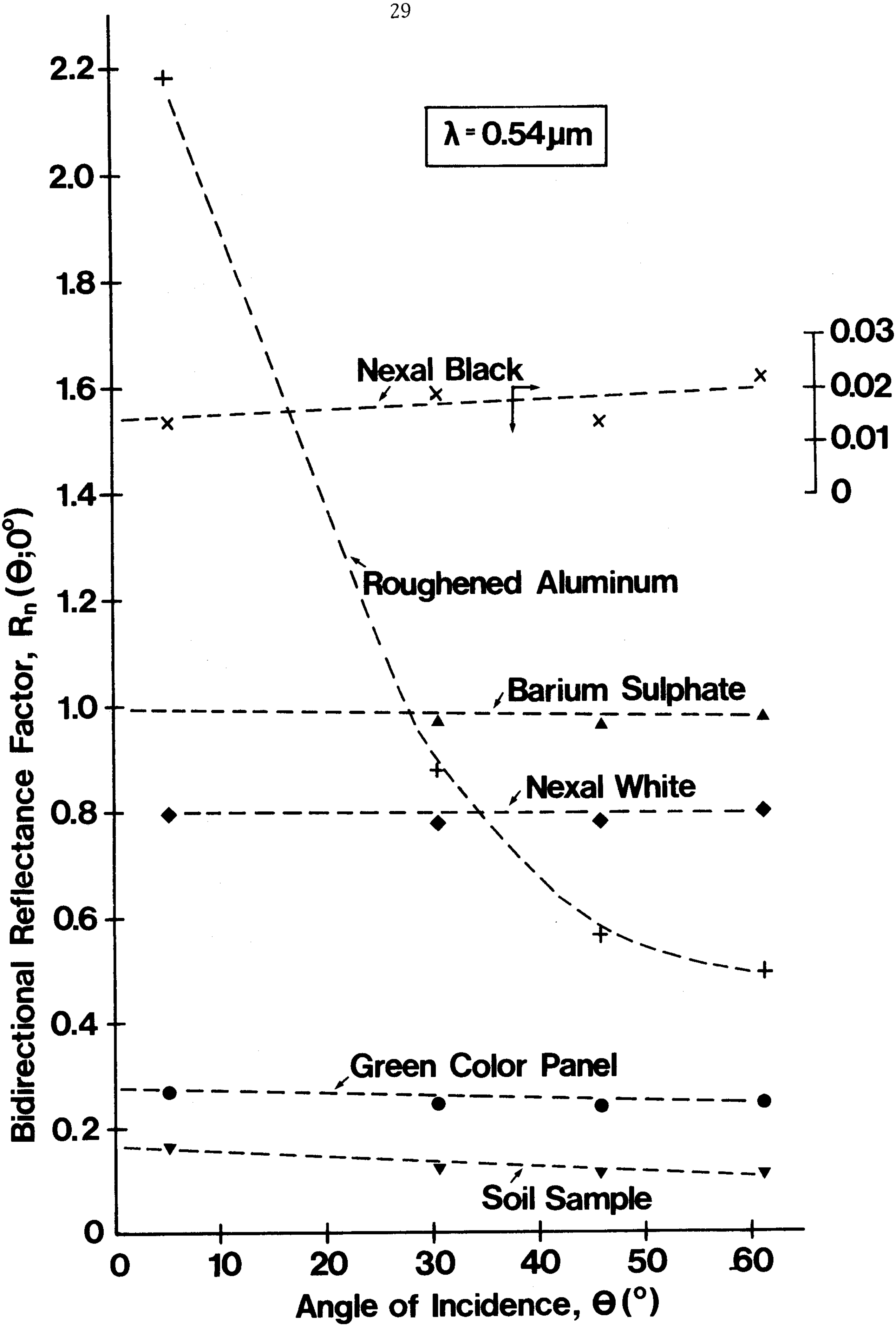

Figure 7. Representation of BRF Measurements, $R_n(\theta;0°)$ for the Six Samples at 0.54 μm--Cartesian Coordinates.

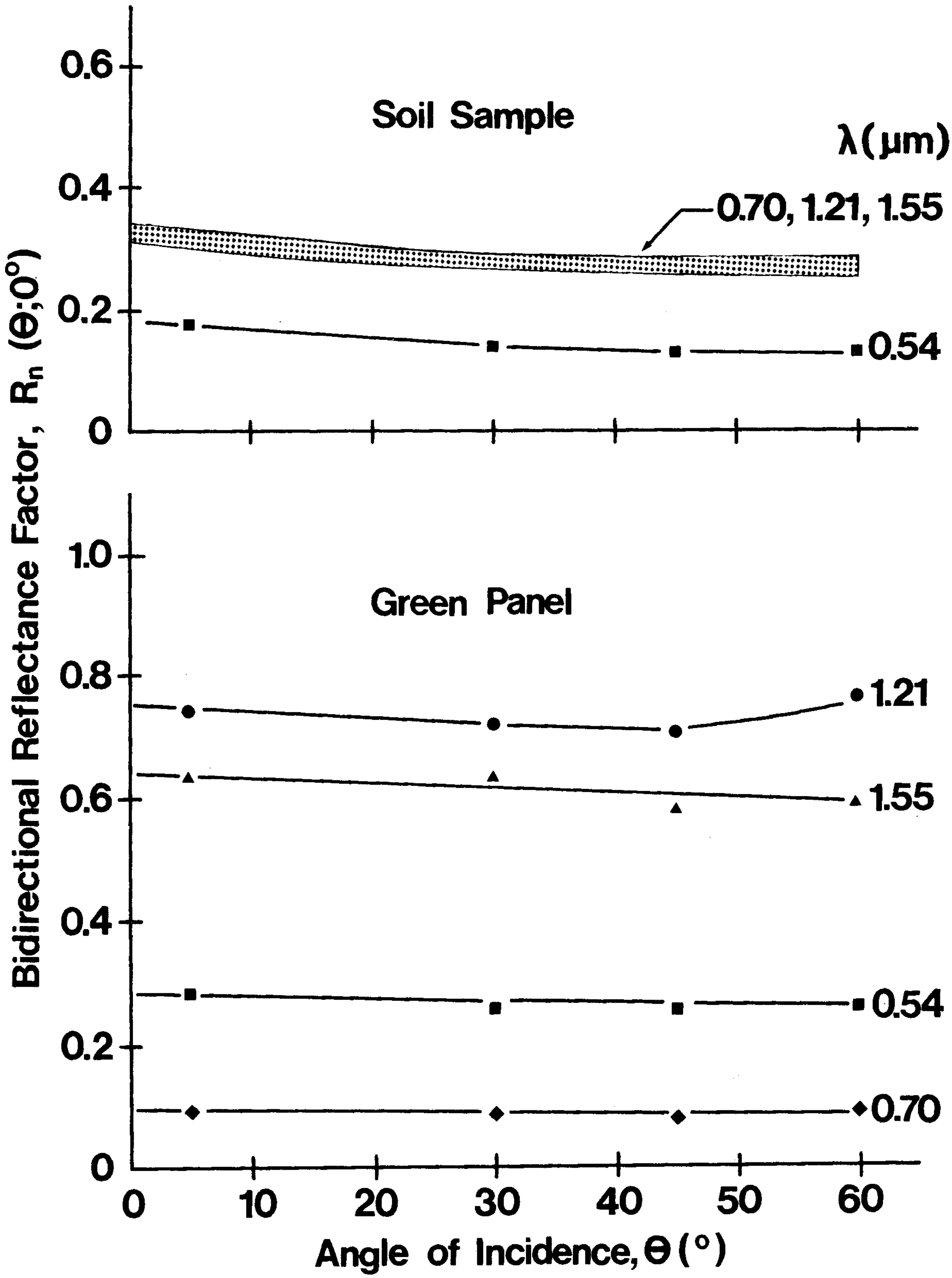

Figure 8. BRF Measurements $R_n(\theta;0°)$, for the Soil Sample and Green Color Panel at Wavelengths λ = 0.54, 0.70, 1.21, 1.55 µm.

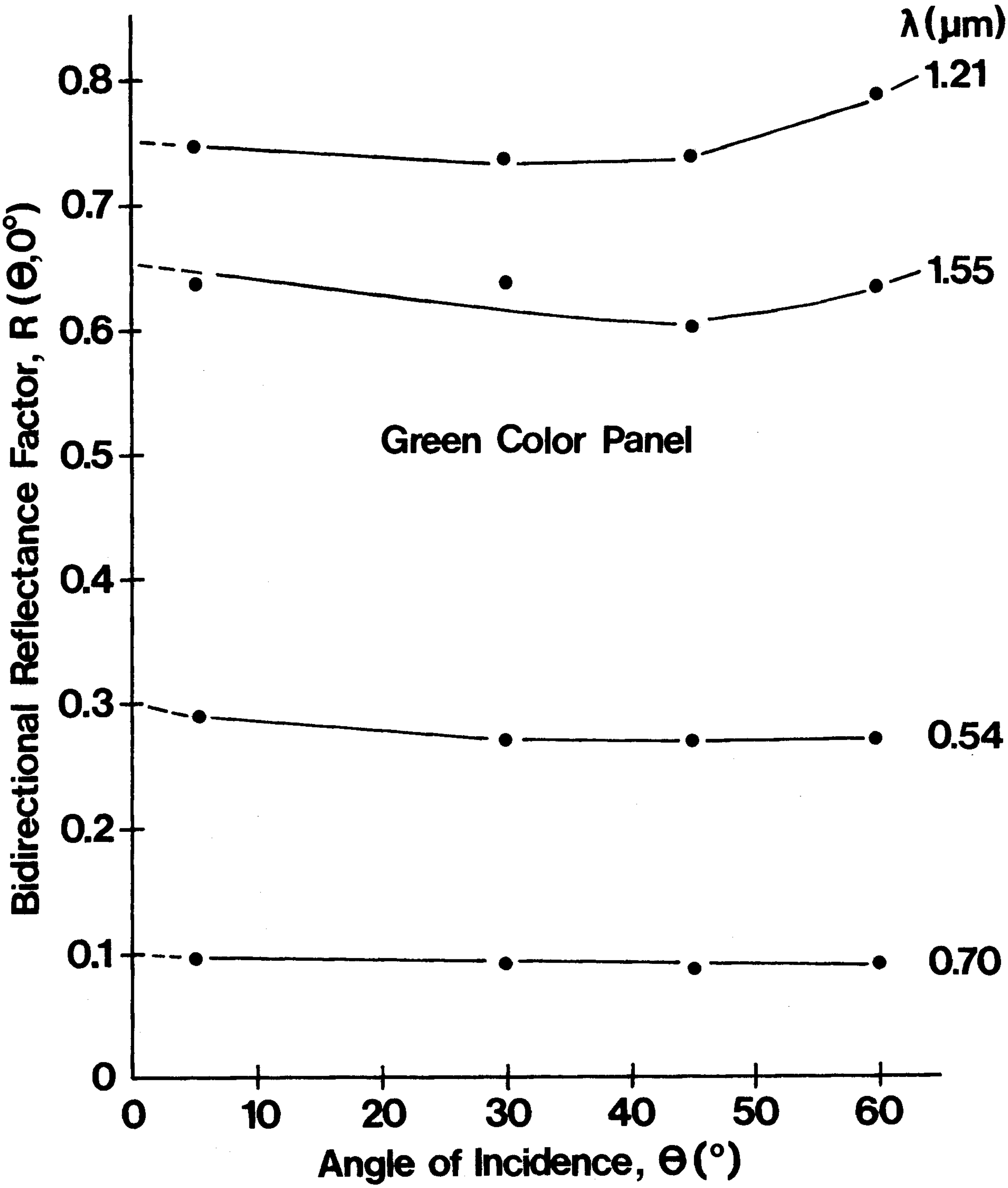

Figure 9. BRF Measurements, R(θ;0°), for the Green Color Panel at Wavelengths, λ = 0.54, 0.70, 1.21, 1.55 µm.

for ideal dielectric materials which predicts that directional reflectance will go toward unity for grazing conditions. The higher the BRF value, the more nearly the sample is acting as an ideal dielectric. From this limited set of data, it is difficult to draw any firm conclusions whether the curvature effect is indeed dielectric phenomena or a systematic error as a result of stray light, for example. Since the BRF is a ratio measurement, and stray light is an additive effect, the systematic errors will be very much dependent upon the magnitude of the sample bidirectional reflectance and therefore the BRF. The evidence available would suggest further critical experiments are called for before giving full confidence to BRF measurements at higher angles of incidence beyond 45°.

Some convicing evidence of reliable BRF/Reflectometer performance comes from comparison of BRF data with measurements of directional hemispherical reflectance factor, $R(6°;2\pi)$, obtained from the Beckmann DK-2 integrating sphere reflectometer. The results of the intercomparison for the green color panel are summarized in Table 1. The first two columns are reflectance factor measurements from the BRF/Reflectometer. The first column is the BRF for the geometric condition (5°;0°) while the second column is the BRF which has been obtained by integration or $R(\theta;0°)$ over the hemisphere according to Equation [29] using the reciprocity relation of Equation [30]. It should be noted that only values for $R(\theta;0°)$ with $\theta \leq 60°$ could be measured and it was necessary to extrapolate the data for the range $60° < \theta \leq 90°$. This was done graphically resulting in a slight upward linear curve.

If the green color panel were a perfect diffuser, the first two columns of Table 1 representing BRF/Reflectometer results would be identical. The differences, less than 0.01 reflectance unit, are too small to be

Table 1

Comparison of Reflectance Measurements, Green Color Panel, by the Beckmann DK-2A Reflectometer and the BRF/Reflectometer

	BRF/Reflectometer		Beckmann
λ(μm)	R(5°;0°)	R(0°;2π)[2]	R(6°;2π)[1]
0.54 ± 0.01	0.287	0.274	0.289 ± 0.01
0.70 ± 0.025	0.097	0.092	0.090 ± 0.01
1.21 ± 0.02	0.749	0.755	0.745 ± 0.007
1.55 ± 0.04	0.636	0.624	0.648 ± 0.01

Notes: 1. Measurements of 3-13-73 [Reference: MgO] and 10-9-75 [Reference: $BaSO_4$]. Uncertainty expressed is a consequence of the uncertainty in the wavelength at which the measurements are being compared.

2. Reflectance factor computed using measured BRF values as a function θ, Equations [29] and [30].

considered significant leading to the conclusion the material is indeed diffuse within the limits of our concern.

The third column of Table 1 represents the directional hemispherical reflectance factor $R(6°;2\pi)$ for the green color panel as directly measured by the Beckmann DK-2A Integrating Sphere Reflectometer. The uncertainties associated with the reported values are a consequence of uncertainty in identifying the wavelength at which the measurement value is to be indicated. In the visible region, the green panel has considerable spectral character resulting in some ambiguity as to the precise wavelength position at which the curve should be read.

The conclusion to be drawn from the comparison of Table 1 is the two instruments based upon different measurement methods do provide satisfactory results within 0.01 to 0.02 reflectance units or expressed as 1% to 2% reflectance full scale. This comparison should be carefully qualified because of two factors. First, the sample surface is very diffuse which eliminates several possible sources of error for both instruments. Second, the integration performed by Equation [28] for the BRF/Reflectometer results relies on extrapolated estimates for the directional range of $60° \leq \theta \leq 90°$ which contains nearly 25% of the reflected flux from a perfect diffuser. Hence, for non-diffuse surfaces where the BRF values for $\theta > 60°$ are not nearly constant, the error in calculating $R(0;2\pi)$ could be substantial.

5. SUMMARY

The remote sensing experimenter should be aware of the directional characteristics of surfaces and recognize that directional reflectance measurements should be carefully qualified. The appropriate reflectance properties have been defined and symbolically represented in a unified manner to clarify current practice and to suggest how the experimenter might choose to discuss his results when directional concepts are involved.

The directional reflectance properties as generated by various types of field and laboratory instruments need to be examined closely before concluding that indeed the results should compare favorably. In this report we have shown the procedure used to intercompare the BRF/Reflectometer with the Beckmann DK-2A Integrating Sphere Reflectometer; for very diffuse surfaces the direct observations are within 1 or 2% reflectance units. For nondiffuse surfaces, to perform the comparison some detailed calculations are necessary.

The BRF/Reflectometer has been evaluated and procedures developed to assure the generation of reliable results. The availability of this facility to study the directional characteristics of large area samples should be an asset to the remote sensing researcher [10, 11, 12].

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APPENDIX A

ABSOLUTE SPECTRAL REFLECTANCE REFERENCE DATA FOR SMOKED MAGNESIUM OXIDE (MgO) AND BARIUM SULFATE (Ba_2SO_4) PAINT [9]

Wave-length (nm)	$BaSO_4$		MgO	
	Pressed powder	Coating of paint (1.0 mm)	Fresh	Aged (2 mo.)
225	0.925	0.905	0.865	0.672
250	0.939	0.932	0.926	0.746
275	0.979	0.962	0.951	0.775
300	0.987	0.983	0.965	0.799
325	0.980	0.978	0.967	0.832
350	0.985	0.982	0.970	0.869
375	0.992	0.980	0.978	0.887
400	0.995	0.986	0.982	0.906
20	0.999	0.988	0.984	0.992
40	0.999	0.980	0.986	0.933
60	0.999	0.993	0.987	0.942
80	0.999	0.993	0.987	0.951
500	0.998	0.992	0.986	0.957
20	0.998	0.992	0.986	0.963
40	0.998	0.993	0.986	
60	0.998	0.992	0.983	
80	0.998	0.992	0.982	
600	0.998	0.992	0.981	
20	0.998	0.992	0.981	
40	0.998	0.992	0.981	
60	0.998	0.992	0.981	
80	0.998	0.992	0.981	
700	0.997	0.992	0.981	
800	0.996	0.992	0.978	
900	0.995	0.989	0.972	
1000	0.991	0.983	0.966	
1100	0.992	0.982	0.965	
1200	0.983	0.973	0.957	
1300	0.980	0.966	0.956	
1400	0.932	0.895	0.939	
1500	0.929	0.896	0.922	
1600	0.944	0.920	0.934	
1700	0.939	0.913	0.935	
1800	0.915	0.892	0.921	
1900	0.829	0.770	0.881	
2000	0.811	0.754	0.854	
2100	0.842	0.765	0.870	
2200	0.842	0.792	0.861	
2300	0.816	0.735	0.847	
2400	0.768	0.713	0.814	
2500	0.703	0.650	0.773	

Appendix B

BIDIRECTIONAL REFLECTANCE FACTOR MEASUREMENTS

on Six Test Samples *

		$R_n(\theta;\theta')$ / $R(\theta;\theta')$				
	$(\theta;\theta')$	(5,0)	(30,0)	(45,0)	(60,0)	(30,30)
Sample**	λ(μm)					
Barium Sulphate	0.54	1.000 1.000	0.977 1.000	0.970 1.000	0.988 1.000	1.114 1.000
	0.70	1.000 1.000	0.976 1.000	0.970 1.000	0.990 1.000	0.893 1.000
	1.21	1.000 1.000	0.980 1.000	0.962 1.000	0.976 1.000	0.905 1.000
	1.55	1.000 1.000	0.998 1.000	0.970 1.000	0.939 1.000	0.875 1.000
White Paint	0.54	0.802 0.802	0.787 0.805	0.794 0.819	0.819 0.829	0.866 0.777
	0.70	0.806 0.806	0.795 0.814	0.800 0.824	0.832 0.841	0.704 0.789
	1.21	0.763 0.763	0.741 0.756	0.737 0.767	0.763 0.782	0.663 0.732
	1.55	0.722 0.722	0.706 0.707	0.691 0.712	0.694 0.739	0.608 0.695
Black Paint	0.54	0.014 0.014	0.019 0.014	0.014 0.014	0.014 0.014	0.019 0.019
	0.70	0.022 0.022	0.022 0.023	0.023 0.024	0.026 0.026	0.022 0.025
	1.21	0.026 0.026	0.026 0.027	0.027 0.028	0.028 0.029	0.028 0.031
	1.55	0.028 0.028	0.028 0.028	0.028 0.029	0.029 0.031	0.024 0.028

Green Panel	0.54	0.287 0.287	0.263 0.269	0.261 0.269	0.267 0.271	0.235 0.211
	0.70	0.097 0.097	0.089 0.091	0.082 0.085	0.091 0.091	0.083 0.093
	1.21	0.749 0.749	0.722 0.737	0.710 0.739	0.768 0.786	0.652 0.720
	1.55	0.636 0.636	0.638 0.639	0.585 0.603	0.597 0.635	0.539 0.616
Roughened Aluminum Sheet	0.54	2.181 2.181	0.892 0.911	0.591 0.610	0.455 0.471	0.286 0.256
	0.70	1.980 1.980	0.952 0.975	0.574 0.592	0.470 0.474	0.277 0.311
	1.21	2.870 2.870	1.080 1.100	0.690 0.718	0.493 0.505	3.090 3.414
	1.55	3.100 3.100	1.122 1.125	0.702 0.723	0.530 0.564	3.980 4.550
Soil	0.54	0.182 0.182	0.146 0.149	0.136 0.140	0.134 0.136	- -
	0.70	0.319 0.319	0.277 0.284	0.267 0.275	0.268 0.270	- -
	1.21	0.325 0.325	0.298 0.305	0.284 0.295	0.294 0.301	
	1.55	0.331 0.331	0.292 0.292	0.279 0.287	0.257 0.274	

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* Nomenclature, See also Section 2(2) for property definitions

$$R(\theta;\theta') = f(\theta;\theta')/f_s(\theta;\theta')$$

$$R_n(\theta;\theta') = f(\theta;\theta')/f_s(5;0)$$

where f_s is the BRDF of the reference standard, barium sulfate

**See Section 4(1) for sample characterization.