POLARIZED RADIANCE. VOLUME III: WAVELENGTH DEPENDENCE OF POLARIZED BIDIRECTIONAL REFLECTANCE

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Environmental Research Institute of Michigan

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POLARIZED RADIANCE VOL III: WAVELENGTH DEPENDENCE OF POLARIZED BIDIRECTIONAL REFLECTANCE

Prepared by

Environmental Institute of Michigan
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Ann Arbor, Michigan

May 1974

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The work reported herein was conducted by the Environmental Research Institute of Michigan for the USA Ballistic Research Laboratories, Aberdeen Proving Ground, MD 21005 under Contract No. DAAD5-72-C-0246. Dr. Lawrence VandeKieft is Technical Monitor. Contracts and grants to the Institute for the support of sponsored research are administered through the Office of Contracts Administration.

Volume III of this report provides the Ballistic Research Laboratories with a method for extracting information from a limited set of directional and bi-directional reflectance measurements so as to provide a wavelength-corrected input to the volume component of the bidirectional reflectance model described in Volume I. It is shown that the surface component of the bidirectional reflectance has little wavelength dependence for the materials studied from 0.63μm through 3.39μm. Data resulting from extensive measurements performed

### Key Words
- Bidirectional Reflectance
- Wavelength Dependence
- Polarized Reflectance
- Modeling

### Abstract
Volume III of this report provides the Ballistic Research Laboratories with a method for extracting information from a limited set of directional and bi-directional reflectance measurements so as to provide a wavelength-corrected input to the volume component of the bidirectional reflectance model described in Volume I. It is shown that the surface component of the bidirectional reflectance has little wavelength dependence for the materials studied from 0.63μm through 3.39μm. Data resulting from extensive measurements performed...
Abstract

at 0.63μm, 1.06μm, 3.39μm and 10.6μm under this contract are included and are used for the model validation which is also described.
FOREWORD

The work reported herein, covering the period 10 April 1972 to 31 May 1973, was carried out by the Infrared and Optics Division of the Environmental Research Institute of Michigan (formerly the Willow Run Laboratories of The University of Michigan), Ann Arbor, Michigan. The work was performed under Contract DAAD05-72-C-0216 for the Army Ballistic Research Laboratories, and was done in three parts, each of which represent one volume.

The three volumes are:

I  - Polarized Bidirectional Reflectance With Lambertian or Non-Lambertian Diffuse Component.
II - Polarized Spectral Emittance From 4 to 14 μm.
III - Wavelength Dependence of Polarized Bidirectional Reflectance.

The internal number of volume III of this report is 192500-1-T(III).
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1.0 INTRODUCTION

The comprehensive bidirectional reflectance modeling which has been described in Volume I of this report [1] was performed without regard to wavelength dependence. Measurements were made at 1.06 μm, and model calculations were made on the basis of the fixed bistatic data of those measurements plus the assumption of a purely real index of refraction, \( n = 1.65 \).

Based on measurements made under other contracts [2] there was, at the outset of this effort, reason to believe that the surface reflectance has no discernible wavelength dependence between .63 μm and 1.06 μm. The volume component, however, does.

The foregoing statements are supported by Figures 1 - 4 where the spectral bidirectional reflectance for a green paint is given in two different source-receiver geometries and with two different source polarizations in each case.

Figures 1 and 2 illustrate the situation for a specular geometry with \( \theta = \theta_r = 55^\circ \). For the perpendicular source polarization (Figure 1) the parallel-polarized receiver return is about two orders of magnitude below that of the perpendicular-polarized receiver. In this case, the surface reflectance \((\rho_{\parallel,\parallel} - \rho_{\perp,\parallel})\) (see Volume I, [1]) is approximately the same as the like-polarized component \((\rho_{\parallel,\parallel})\) which is seen to be essentially flat between 0.63 and 1.06 μm. (If the cross-polarized component is subtracted out, it becomes even flatter.) Therefore, with a perpendicular-polarized source, the bidirectional surface reflectance in a specular geometry for this sample appears wavelength independent from .63 to beyond 1.06 μm.

The spectral return with a parallel-polarized source (Figure 2) looks different. This is so because at \( \theta = 55^\circ \) we are very close to the Brewster angle and the reflectance from a parallel-polarized source nears its minimum. However, in this case too, when the surface component is calculated by subtracting the cross-polarized component from the like-polarized component \((\rho_{\parallel,\parallel} - \rho_{\parallel,\perp})\) it is seen to be essentially wavelength independent.
FIGURE 1  SPECTRAL BIDIRECTIONAL REFLECTANCE FOR GREEN PAINT
(SAMPLE NO. 1027) FOR A SPECULAR GEOMETRY WHERE $\theta_i = 55^0$
FIGURE 2 SPECTRAL BIDIRECTIONAL REFLECTANCE FOR GREEN PAINT (SAMPLE NO. 1027) FOR A SPECULAR GEOMETRY WHERE $\theta_i = 55^\circ$
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between .63 and 1.06 μm. However, it is obvious in both Figure 1 and Figure 2 that there is a spectral dependence in the volume, or cross-polarized, component itself.

The same sample is described in Figure 3 and 4 with a different source-receiver geometry; this time θ_1 = 0 and θ_r = 50°. Now the case with perpendicular source polarization (Figure 3) looks almost identical to that with parallel source polarization. In both cases, the surface component (ρ_α - ρ_α) is clearly flat throughout the graph, while the volume (cross-polarized) component contains the spectral dependence. It will be seen in Section 2 that a similar situation exists for the samples studied in this work.

The program for this modeling effort was to assume that the wavelength variation of the volume component of the bidirectional reflectance was the same as that for the directional reflectance. If the bidirectional volume reflectance for a given surface is known at one wavelength and the directional reflectance can be obtained at that wavelength and a second wavelength, then the bidirectional volume reflectance for the second wavelength can be obtained from:

\[
\rho'_V(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_2) = \frac{\rho_B(\lambda_2)}{\rho_B(\lambda_1)} \rho'_V(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_1)
\]

Description of the model is given in Section 3 and of the validation in Section 4. Measurement data are discussed in Section 2.

2.0 MEASUREMENTS

The purpose of the measurement program was to obtain sufficient data to validate the model and to extract input information, based on wavelength dependence, for the RHOPRIME program described in Volume I. In particular, it was important to determine a) the surface reflectance dependence on wavelength in the wavelength region of .63 μm to beyond 3.39 μm and, b) whether the assumption that the bidirectional reflectance varies as the directional reflectance in the volume component is valid.
To accomplish the above objectives extensive measurements were performed on three different sample surfaces at four different wavelengths. The samples are code-numbered: A01610, A02022, and A02023. All are metallic surfaces coated with varying shades and textures of green paint.

The measurements carried out under this contract were bidirectional reflectance measurements performed on the ERIM gonioreflectometer [3]. However, in order to determine directional reflectance ratios, it was necessary to have direct directional reflectance measurement data. Such measurements have been performed by ERIM on the same samples with a Beckman DKII spectrometer under other contracts. (Samples A02022 and A02023 were measured under Contract DAAF03-72-C-0115 with Rock Island Arsenal [4] while Sample A01610 was measured under Contract F33615-68-C-1281 with the Air Force Avionics Laboratory [5].)

2.1 Beckman Spectrometer Directional Reflectance Measurements

The purpose of these measurements was to obtain data for $p_D(\lambda)$ so that the ratio of the directional reflectances at two different wavelengths could be used to predict the bidirectional reflectance at one of the wavelengths, given the bidirectional reflectance at the other. (The description of the model is detailed in Section 3.)

Figures 5, 6, and 7 show the directional reflectance measurements from .4 \( \mu \)m to 2.6 \( \mu \)m for samples A01610, A02022 and A02023, respectively. All three samples are shades of green in color and should be expected to increase reflectance sharply in the green wavelength range. That this happens between about .49 and .53 \( \mu \)m is shown in all three figures. In the infrared, A01610 becomes extremely bright at about .75 \( \mu \)m and remains highly reflecting to the 2.6 \( \mu \)m limit of the Beckman measurement. Both A02022 and A02023 show no further rise beyond the increase at .49 \( \mu \)m.

In all three cases, reflectance includes both surface and volume contributions and further reduction had to be performed before the data could be used.
2.2 Gonioreflectometer Bidirectional Reflectance Measurements

Data from the bidirectional reflectance measurements are given in Appendix A. When using the bidirectional reflectance data, the following observations should be noted:

1. There is no significant variation of the surface component of \( \rho \) as a function of wavelength between 0.63 \( \mu \text{m} \) and 1.06 \( \mu \text{m} \). (There are, however, significant variations in the volume components in the same spectral region.) That a linear relation is reasonable between 0.63 \( \mu \text{m} \) and 10.6 \( \mu \text{m} \) is discussed in section 4 where it is shown that for sample AO 1610, the greatest error is about 40\% and for the other two samples, the greatest error is about 17\%. Therefore, we conclude that for the surface component there is no more than a weak wavelength dependence which is approximately linear with a small enough slope that variations are not significant between 0.63 \( \mu \text{m} \) and 10.6 \( \mu \text{m} \).

2. For Samples A01610 and A02022, the volume component varies with wavelength and the measurements are unambiguous and suitable for parameter extraction at 0.63 \( \mu \text{m} \) and 1.06 \( \mu \text{m} \). However, at 3.39 \( \mu \text{m} \) and 10.6 \( \mu \text{m} \), the volume component falls to below the noise level of the system and hence cannot be used for validation. At 0.63 \( \mu \text{m} \) the volume component for Sample A02023 is also below the system noise and therefore this sample was not used in the validation. The result is that two samples (A01610 and A02022) were used for model validation at two wavelengths (0.63 \( \mu \text{m} \) and 1.06 \( \mu \text{m} \)).

3. Difficulties encountered in aligning the receiver polarization analyzer for the 3.39 \( \mu \text{m} \) measurements make necessary the following corrections when working with the data:
   a) All \( \pm 45^\circ \) source polarization data must be multiplied by a scale factor of 0.38.
   b) Polarization symbols on the 3.39 \( \mu \text{m} \) data are incorrect because of the alignment problems. Table 1 shows what the symbols, as they are, represent and what the correct symbols (with their representative polarizations) should be.
<table>
<thead>
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<th>Present Code</th>
<th>Correct Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>* (⊥, 45)</td>
<td>◆ (⊥, -45)</td>
</tr>
<tr>
<td>□ (</td>
<td></td>
</tr>
<tr>
<td>X (45, ⊥)</td>
<td>K (</td>
</tr>
<tr>
<td>B (45, 45)</td>
<td>M (-45, -45)</td>
</tr>
<tr>
<td>⊙ (45,</td>
<td></td>
</tr>
<tr>
<td>◆ (⊥, -45)</td>
<td>* (⊥, -45)</td>
</tr>
<tr>
<td>K (</td>
<td></td>
</tr>
<tr>
<td>A (-45, ⊥)</td>
<td>X (45, ⊥)</td>
</tr>
<tr>
<td>M (-45, -45)</td>
<td>B (45, 45)</td>
</tr>
<tr>
<td>S (-45,</td>
<td></td>
</tr>
</tbody>
</table>
c) Nominal receiver polarization angles are presented with the actual polarization angles in Table 2. Because the receiver is not really at 90° (||) when so referred to, there is no pure cross-polarized measurement with the source at 0° (\perp). Therefore, there appears to be a larger cross-polarized component than there should be in these cases. The increase, however, really represents that part of the 0° polarized return which is not stopped by the analyzer and should be disregarded.

4. In the fixed bistatic data for Sample A02022 at 3.39 μm it should be noted that the \perp component truncates at about \( \theta_r = 7^\circ \) because of instrumental saturation.

3.0 MODEL DESCRIPTION

The wavelength dependence model for the volume component of the bidirectional reflectance is based on the assumption that the volume bidirectional reflectance varies with wavelength in the same manner as the directional reflectance. (This assumption has been discussed in [2].) The plausibility of this assumption is borne out by the measurements as described in Section 2. Therefore, if we are able to obtain the directional reflectance, \( \rho_D(\lambda) \), at two wavelengths, we can take the ratio of the two and say that the volume bidirectional reflectance varies by the same ratio. In mathematical terms:

\[
\frac{\rho'_v(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_1)}{\rho'_v(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_2)} = \frac{\rho_D(\lambda_1)}{\rho_D(\lambda_2)} \frac{\rho'_v(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_2)}{\rho'_v(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_1)}
\]

where \( \rho'_v \) is the volume component of the bidirectional reflectance.

As shown in Volume I, the volume component of the bidirectional reflectance always contains a multiplicative factor, \( \rho_v \) in the non-Lambertian case and \( \rho_x \) in the Lambertian case, where \( \rho_v \) (or \( \rho_x \)), is a constant model parameter which is extracted from a fixed-bistatic bidirectional reflectance scan.
<table>
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<th>Nominal Polarisation Angle</th>
<th>FIXED BISTATIC</th>
<th>Actual Polarisation Angle</th>
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<tr>
<td>0 (⊥)</td>
<td></td>
<td>-7</td>
</tr>
<tr>
<td>-45</td>
<td></td>
<td>-58.5</td>
</tr>
<tr>
<td>-90 (</td>
<td></td>
<td>)</td>
</tr>
<tr>
<td></td>
<td>IN-PLANE</td>
<td></td>
</tr>
<tr>
<td>0 (⊥)</td>
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<td>0</td>
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<tr>
<td>+45</td>
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<td>+41.5</td>
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<td>+90 (</td>
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Therefore, the wavelength dependence is included in the model as a wavelength dependent variation of the parameter, \( \rho_v \) (or \( \rho_x \)), which is extracted from directional reflectance data. No modification of the model as described in Volume I is necessary.

**Parameter Extraction**

The model depends upon the assumption that the surface bidirectional reflectance (also the surface directional reflectance) varies linearly with wavelength. Under this assumption, if one knows the surface reflectance at two points, it is possible to interpolate at any point in between. Therefore, it is possible to eliminate the surface component from the directional reflectance at any point. The volume directional reflectance is then used to construct the ratio of directional reflectances at two wavelengths. This ratio is then used to derive the bidirectional reflectance at one of the wavelengths if it is known at the other.

The parameter to be extracted consists of the directional reflectance \( \rho_D \) at two different wavelengths for a material of interest. It is clear that measurements on a spectrometer such as the Beckman DKII are ideal for this purpose, if they can exclude the surface component or if it can be determined independently and eliminated.

Alternatively, the same information can be extracted from bidirectional reflectance measurements, preferably from a bidirectional scan where the source is normal to the target plane \( (\theta_1 = 0) \). In this case one works only with the cross-polarized components \( (\rho'_1 \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel 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\parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \parallel \par
3.1 Extraction From Directional Reflectance Data

It has been stated earlier that the directional reflectance measurement includes a surface reflection component which must be eliminated. This can be done if independent data are available from which the surface component can be taken. In the case of this work, the information is included in the bidirectional reflectance measurement of the surface component, i.e. the like-polarized component ($\rho'_{ll}$ or $\rho'_{11}$). However, there is a non-surface contribution present in the like-polarized components which must first be subtracted out [1].

Also, since an unpolarized directional reflectance can be regarded as a sum of perpendicular and parallel polarized reflectances, we average over both of these cases in the bidirectional reflectance data and obtain:

$$\rho'_{\text{surface}} = \frac{\rho'_{ll} + \rho'_{|| ||}}{2} - \frac{\rho'_{l||} + \rho'_{|| l}}{2}$$

where $\rho'_{\text{surface}}$ is the surface contribution of the bidirectional reflectance. To obtain the surface contribution to the directional reflectance, $\rho'_{\text{surface}}$ must be integrated or summed over the entire hemisphere so that, [3]:

$$\rho_{\text{surface}} = \int \rho'_{\text{surface}}(\theta, \phi, \theta_r, \phi_r) \sin \theta_r \cos \theta_r d\phi_r d\theta_r$$

If we now make the reasonable assumption that there is no $\phi$ dependence in $\rho'$, then:

$$\rho_{\text{surface}} = 2\pi \int \rho'_{\text{surface}}(\theta, \phi, \theta_r, \phi_r) \sin \theta \cos \theta \, d\theta$$

Since there is no easily expressible analytical form for $\rho'$ it is necessary to resort to numerical or graphical methods. The method actually used was graphical and is described in [3]. Using a bidirectional reflectance scan with $\theta_1 = 0$, the functions
\[
\frac{\rho'(\theta_r) + \rho'(\phi_r) - \rho'(\phi_r) - \rho'(\theta_r)}{2} \sin \theta_r \cos \theta_r
\]

was plotted on linear graph paper every 5° for each wavelength of interest. A planimeter was then used to obtain a relative area (or integration) for each plot.

Let \( \rho_d(\lambda_1) \) = area of volume component (cross-polarized) plot for wavelength \( \lambda_1 \).

\( \rho_s(\lambda_1) \) = area of surface component (like-polarized minus cross-polarized) plot for wavelength \( \lambda_1 \).

Then:

\[
\rho_D(\lambda_1) = \left[ \frac{\rho_d(\lambda_1)}{\rho_s(\lambda_1) + \rho_d(\lambda_1)} \right] \rho_{DB}(\lambda_1)
\]

where

\( \rho_D(\lambda_1) \) is the true directional reflectance for \( \lambda_1 \), and

\( \rho_{DB}(\lambda_1) \) is the directional reflectance including the surface component as measured in the spectrometer.

Therefore:

\[
\rho'(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_1) = \frac{\rho_D(\lambda_1)}{\rho_D(\lambda_2)} \rho'_V(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_2)
\]

\[
= \left[ \frac{\rho_d(\lambda_1)}{\rho_d(\lambda_1) + \rho_s(\lambda_1)} \right] \rho_{DB}(\lambda_1) \cdot \rho'_V(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_2)
\]

Note that to find \( \rho'_V \) at some \( \lambda_j \) between \( \lambda_1 \) and \( \lambda_2 \), we would first find \( \rho_s(\lambda_j) \) by linear interpolation between \( \rho_s(\lambda_1) \) and \( \rho_s(\lambda_2) \). Then assuming that \( \rho_D(\lambda_1), \rho_D(\lambda_2) \) and \( \rho'_V(\lambda_1) \) are known, we can find \( \rho_D(\lambda_1) \) and can calculate:

\[
\rho'_V(\lambda_j) = \frac{\rho_D(\lambda_1)}{\rho_D(\lambda_1) \rho'_V(\lambda_1)}.
\]
3.2 Extraction From Bidirectional Reflectance Data

In this case we use only the bidirectional reflectance scan where the source is normal to the target plane ($\theta_1 = 0$).

The function to be integrated is:

$$\rho_D = (\rho_{\parallel} || + \rho_{\perp} ||) \sin\theta_r \cos\theta_r$$

Once again the integration is performed graphically after plotting values for the above expression every 5° using the $\theta_1 = 0$ bidirectional data. After repeating the procedure for a second wavelength, the expression can be written:

$$\rho_V^{'\lambda_1}(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_1) = \frac{\rho_D^{'\lambda_1}(\lambda_1)}{\rho_D^{'\lambda_2}(\lambda_2)} \rho_V^{'\lambda_1}(\theta_1, \phi_1, \theta_r, \phi_r; \lambda_1)$$

In both this procedure and the previous one in which directional data were used the wavelength factor is actually applied to the RHOPRIME program input, $\rho_V$ or $\rho_X$ (see Volume I), so that

$$\rho_V^{'\lambda_1} = \frac{\rho_D^{'\lambda_1}(\lambda_1)}{\rho_D^{'\lambda_2}(\lambda_2)} \rho_V^{'\lambda_1}(\lambda_2)$$

and similarly for $\rho_X$.

4.0 MODEL VALIDATION

In Figures 8, 9, and 10, the justification for assuming a linear relation between wavelength and surface directional reflectance is shown. Figure 8 shows directional surface reflectance as a function of wavelength for sample AO 1610. (By directional surface reflectance we mean the surface component of the bidirectional reflectance integrated over the hemisphere.) Figures 9 and 10 represent samples AO 2022 and AO 2023 respectively. In all cases the reflectances are normalized so that the value at 0.63 $\mu$m is 1. A straight line is drawn between reflectance values at 0.63 $\mu$m and 10.6 $\mu$m. For sample AO 1610, the largest deviation from linearity is about 40%. For sample AO 2022 the fit to linearity is never worse than 17%, and for AO 2023, never worse than 16%.

As pointed out earlier, validation was done only at 0.63 and 1.06 $\mu$m since there was no measurable cross-polarized reflectance for any of the
FIGURE 10. Surface Component of Spectral Directional Reflectance For A02023
samples at 3.39 or 10.6 μm. Therefore validation in this case is a confirmation that the relationship,

$$\rho_V(\lambda_1) = \frac{\rho_D(\lambda_1)}{\rho_D(\lambda_2)} \rho_V(\lambda_2)$$

is valid based on comparison with measurements. If it had turned out that there was a measurable volume component at 3.39 μm the interpolation scheme described in Section 3 could have been more thoroughly validated. Also only samples A01610 and A02022 were used because A02023 had no measurable cross-polarized reflectance at 0.63 μm.

Fixed bistatic bidirectional reflectance scans at both wavelengths (Figures 11, 12, 13 and 14) indicate that both samples follow a non-Lambertian volume reflectance at 0.63 μm. At 1.06 μm the volume component appears to be quite flat for both samples and so in the validation it was assumed that the volume component was Lambertian. Therefore in running the model we use ρV for 0.63 μm and ρX for 1.06 μm as discussed in Volume 1.

In running the RHOPRIME program, only the cross-polarized contribution was calculated since as stated earlier, only the cross-polarized component has significant wavelength dependence in the spectral region between 0.63 μm and 3.39 μm.

The validation was performed two ways for each sample. In one case, ρX was determined from the fixed bistatic data at 1.06 μm and ρV for 0.63 μm was then calculated from:

$$\rho_V(0.63) = \frac{\rho_D(0.63)}{\rho_D(1.06)} \rho_X(1.06)$$

In the other case ρV was determined from the fixed bistatic data at 0.63 μm and ρX for 1.06 μm was then calculated from:
$\lambda = .63$
$\phi_i = \phi_n + -1.7$
$\phi_f = .0$

**FIGURE 11a**
AO 1610

**BIDIRECTIONAL REFLECTANCE (STER. -1)**

$\phi_n = .00 \quad \phi_n = 180.00$

90. 60. 30. 0. 30. 60. 90.
\[ \lambda = 0.63 \]
\[ \phi_1 = \phi + 1.7 \]
\[ \phi_1 = 180.0 \]

**Figure 11b**

**Bi-directional Reflectance (Stern.)**

\[ \theta_0 = 180.00 \]

\[ \theta_0 = 0.00 \]

(Degrees)
$\lambda = 1.06$

$\phi_I = \phi_R + 1.7$

$\phi_I = 0$

\[ \text{Bi-directional Reflectance (STRA.-)} \]

\[ \text{(DEGREES)} \]

\[ \phi_h = 0.00, \quad \phi_h = 35, \quad \phi_h = 180.00 \]
\[ \lambda = 1.06 \]
\[ \phi_i = \phi_r + 1.7 \]
\[ \phi_f = 180.0 \]

**FIGURE 12b**

AO 1610
\[ \lambda = .63 \]
\[ \phi_1 = \phi_R + 1.7 \]
\[ \phi_1 = 0.0 \]

**FIGURE 13a**

A0 2022
\[ \lambda = 0.63 \]
\[ \phi_1 = \phi_2 = 1.7 \]
\[ \phi_3 = 180.0 \]

FIGURE 13b
AO 2022

BIODIRECTIONAL REFLECTANCE (STER.\(^{-1}\))

\( \theta_R = 0.00 \) \( \phi_R = 38 \) \( \phi_R = 180.00 \)

90. 60. 30. 0. 30. 60. 90.
$\lambda = 1.06$

$\phi_j = \phi_n + 1.7$

$\phi_1 = 0$

**Figure 14a**

AO 2022
Figure 14b

\[ \lambda = 1.06 \]
\[ \phi_1 = \phi_2 + 1.0 \]
\[ \phi_3 = 180.0 \]

Bidirectional Reflectance (sterad⁻¹)

\[ \phi_n = \theta_n \text{ (degrees)} \]
\[ \phi_n = 180.00 \]

Graph showing the relationship between bidirectional reflectance and angle of incidence.
Results were then compared to the measured data for two different source angles, \( \theta_1 = 0^\circ \) and \( \theta_1 = 40^\circ \). For both samples it was decided that behavior was most nearly non-Lambertian at 0.63 \( \mu \text{m} \) and most nearly Lambertian at 1.06 \( \mu \text{m} \).

Figure 15 shows the measured data for sample A01610 with "parallel"-polarized source* at \( \theta_1 = 0^\circ \) and at 0.63 \( \mu \text{m} \). Figure 16 shows the calculation for the volume component for 0.63 \( \mu \text{m} \) with the \( \rho_v \) value extrapolated from 1.06 \( \mu \text{m} \) data. The agreement is very close. Figures 17 and 18 provide a similar comparison for \( \theta_1 = 40^\circ \). Figures 19 - 22 again provide similar comparisons for sample A02022. It should be noted that between 0.63 \( \mu \text{m} \) and 1.06 \( \mu \text{m} \) the wavelength correction is small. As wavelength increases beyond 1.06 \( \mu \text{m} \), however, the cross-polarized component decreases rapidly. (At 3.39 \( \mu \text{m} \) it is effectively zero.) Therefore the wavelength correction will be more important as \( \lambda \) increases beyond 1.06 \( \mu \text{m} \).

*The cross-polarized component for the "parallel"-polarized source is the same as that for the "perpendicular"-polarized source.
\( \lambda = 0.63 \)
\( \phi = 0.0 \)
\( \phi_1 = 180.0 \)

**Figure 15**
AO 1610

**BiDirectional Reflectance (Ster^-1)**

- Plot showing data points at various angles.
- Axes: Degrees (from 0 to 90) and BiDirectional Reflectance (Ster^-1) with log scale.
- Data points are marked at specific angles.
FIGURE 20

\[ \phi_i = 180.0 \]

Bidirectional Reflectance (Ster. \(^{-1}\))

\( \phi_n = 0.0 \quad \phi_i = 180.0 \)

Degrees
\[ \lambda = 0.63 \]
\[ \phi_i = 40.0 \]
\[ \theta_i = 180.0 \]
REFERENCES


APPENDIX A

BIDIRECTIONAL REFLECTANCE DATA FOR SAMPLES
A01610, A02022, A02023 AT 0.63, 1.06, 3.39 AND 10.6 um.

For convenience in using this Appendix, the data are preceded by
an index which outlines the organization and provides page numbers of
specific data sets.
### Bidirectional Reflectance Data With Fixed Bistatic Angle

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Bidirectional Reflectance Data With Variable Bistatic Angle

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\[ \chi = 0.63 \]
\[ \theta_i = \phi_i = -1.7 \]

**BIDIRECTIONAL REFLECTANCE (STER.-1)**

\[ \phi_i = 0.00 \quad \phi_i = 180.00 \]

\[ \phi_i = 0.00 ^{\circ} \quad \phi_i = 180.00 ^{\circ} \]

**Degrees**
A02023 501

\[ \lambda = 0.63 \]

\[ \phi_1 = 0.7 \]

\[ \phi_i = 180.0 \]

BIDIRECTIONAL REFLECTANCE (STER.⁻¹)

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 10^{0} \]

\[ 10^{1} \]

90. 60. 30. 0. 30. 60. 90.

\[ \theta_n = 0.00 \]

\[ \theta_i = 58 \]

\[ \phi_1 = 180.00 \]
\( \lambda = 1.06 \)

\( \phi_1 = 0 \)

\( \phi_2 = 1.7 \)

\( \phi_m = 0.00 \)

\( \phi_m = 180.00 \)
\( \lambda = 1.06 \)

\( \phi = \phi^* - 1.0 \)

\( \phi = 180.0 \)
A02023  703

\[ \lambda = 3.39 \]
\[ \phi_l = \phi_n + 2.0 \]
\[ \phi_l = .0 \]

**Bi-directional Reflectance (STER.-1)**

- **Wavelength (\(\lambda\))**: 3.39
- **Phase Angle (\(\phi_l\))**: \(\phi_n + 2.0\)
- **Phase Center (\(\phi_l\))**: .0

The graph represents bi-directional reflectance as a function of phase angle in degrees. The y-axis represents the reflectance in steradians, while the x-axis shows the phase angle in degrees from 0 to 90 degrees.
\( \lambda = 3.39, \quad \phi_1 = \phi_0 - 2.0, \quad \phi_1 = 180.0 \)

BIODIRECTIONAL REFLECTANCE (STER〜1)

\[ \begin{align*}
\phi_0 &= 0.0 \quad \phi_n = 66 \\
\phi_1 &= 180.0
\end{align*} \]
\( \lambda = 10.60 \)
\( \theta_i = -2.5 \)
\( \theta_f = 180.0 \)

**Diagram Description:**

- **Title:** BIDIRECTIONAL REFLECTANCE (STER.-1)

- **Axes:**
  - X-axis: (DEGREES)
  - Y-axis: \( 10^1 \) to \( 10^{-9} \)

- **Data Points:** Various data points are plotted on the graph, indicating reflectance values at different angles.

- **Key:**
  - \( \theta_n = 0.00 \)
  - \( \theta_n = 180.00 \)
$\lambda = 0.63$

$\phi_i = \phi_r + 1.7$

$\phi_t = 0.0$

 Diagram showing bidirectional reflectance with axes labeled $\phi_h$ from 90 to 0 degrees on the x-axis and bidirectional reflectance (ster. -1) on the y-axis.
\[ \lambda = 0.63 \]
\[ \phi = 1.7 \]
\[ \phi_0 = 180.0 \]
A02023 101

$\lambda = 1.06$

$\eta = \eta^* 1.7$

$\phi = 0.0$

BIDIRECTIONAL REFLECTANCE (STER.-1)

$\phi_{n} = 0.00 \quad \phi_{n} (DEGREES) \quad \phi_{n} = 180.00$
\[ \gamma = 1.06 \]
\[ \phi = -1.0 \]
\[ \phi = 180.0 \]

**Bidirectional Reflectance (Ster^-1)**

- **\( \phi_0 = 0.00 \)**
- **\( \phi_{180} = 180.00 \)**
\[ \chi = 3.39 \]
\[ \phi_1 = \theta_m + 2.0 \]
\[ \phi_t = 0.0 \]
λ = 3.39
θ_i = -2.0
θ_r = 180.0

BIDIRECTIONAL REFLECTANCE (STER.-1)

90. 60. 30. 0. 30. 60. 90.
φ_m = .00 74.00 φ_m = 180.00
\[ \lambda = 10.60 \]
\[ \theta_i = -2.5 \]
\[ \phi_i = 180.0 \]
\( \lambda = 10.60 \)
\( \phi_i = -2.5 \)
\( \phi_f = 90.0 \)

Graph showing bi-directional reflectance (ster.-1) vs. \( \phi_i \) and \( \phi_f \) in degrees with data points at \( \phi_i = 90.00 \) and \( \phi_f = 270.00 \).
\[ \lambda = 10.60 \]
\[ \phi_i = 2.5 \]
\[ \phi_r = 270.0 \]
\[ \lambda = 0.63 \]
\[ \phi_{\lambda} = \phi_{\lambda^+} = 1.7 \]
\[ \phi_{\phi} = 0.0 \]

**BI_DIRECTIONAL REFLECTANCE (STER.\(^{-1}\))**

\[ \theta_{\text{in}} = 0.00 \quad \theta_{\text{out}} = 180.00 \]
\[ \chi = 0.63 \]
\[ \theta = 1.7 \]
\[ \phi_0 = 180.0 \]

**Bidirectional Reflectance (STER.)**

\[ 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{0} \quad 10^{1} \]

\( \phi = 0.00 \quad 80 \quad 180.00 \)

\( \phi \) (Degrees)
$\lambda = 1.06$
$\phi_t = 1.7$
$\phi_i = 0.0$

BIODIRECTIONAL REFLECTANCE (STER. -1)

$10^{-1}$
$10^{0}$
$10^{1}$

90.  60.  30.  0.  30.  60.  90.

$\phi_i = 0.0$  $\phi_i (DEGREES)$  $\phi_i = 180.00$
\[ \lambda = 3.39 \]
\[ \phi_j = \phi_n + 2.0 \]
\[ \phi_i = 0.0 \]
$\lambda = 3.39$
$\phi_i = \phi_r = -2.0$
$\phi_i = 180.0$
$\lambda = 10.60$
$\phi_i = 0.0$
$\phi_i = 2.5$

**Diagram:**

- Title: BIO DIRECTIONAL REFLECTANCE (STER. -1)
- Axes:
  - X-axis: $0^\circ$ to $90^\circ$
  - Y-axis: $10^{-3}$ to $10^{1}$
- Data points and lines indicating reflectance values.
\( \lambda = 10.60 \)
\( \phi_i = \phi + -2.5 \)
\( \phi_i = 180.0 \)
$\lambda = 3.39$
$\phi_1 = \phi_n = 2.0$
$\phi_2 = 0.0$

**Bidirectional Reflectance (Ster.-1)**

$\phi_n = \theta_n$ (DEGREES)

$\phi_n = 180.00$
\( \lambda = 3.39 \)
\( \theta_i = \phi_i + -2.0 \)
\( \phi_i = 180.0 \)
$\lambda = 0.63$
$\phi_s = \phi_n + 1.7$
$\phi_t = 0$

**Diagram**

**Bidirectional Reflectance (Ster. -1)**

- The graph shows the relationship between the angle of incidence and the bidirectional reflectance.
- The data points are plotted on a logarithmic scale.

**Axes**
- X-axis: Angle of incidence (Degrees)
- Y-axis: Bidirectional Reflectance (Ster. -1)

**Data Points**
- Data points are marked at specific angles and reflectance values.

**Legend**
- $\phi_n = 0.00$ (Degrees)
- $\phi_n = 180.00$
\[ \lambda = 0.63 \]
\[ \phi_1 = \phi_0 + 1.7 \]
\[ \phi_0 = 180.0 \]

**Graph**

**Title:** Bidirectional Reflectance (Steradian^-1)

**Axes:**
- **Horizontal Axis:** θ (Degrees)
- **Vertical Axis:** 10^-3 to 10^-1

**Legend:**
- \( \eta = 0.00 \) at 90°
- \( \eta = 180.00 \)
\( \lambda = 1.06 \)
\( \phi_i - \phi_i = -1.7 \)
\( \phi_i = 0 \)

![Graph showing bidirectional reflectance](image-url)
\[ \lambda = 1.06 \]
\[ \phi_i = \phi_n + 1.7 \]
\[ \phi_i = 0.0 \]

**Bidirectional Reflectance (Stef.-1)**

- \( \phi_n = 0.0 \) to \( \phi_n = 180.00 \)

Diagram showing bidirectional reflectance with angular distribution.
$\lambda = 10.60$
$\phi_i = \phi_r = -2.5$
$\phi_t = 90.0$

**BI DIRECTIONAL REFLECTANCE (STER. -1)**

$\phi_r = 90.00 \quad \phi_a (\text{DEGREES}) \quad \phi_a = 270.00$
$\lambda = 0.63$

$\phi_2 = \phi_1 + 1.7$

$\phi_1 = 0.0$

BIDIRECTIONAL REFLECTANCE (STER. -1)

$\theta_R = 0.00$ $\phi_R$ (DEGREES)

$\theta_A = 180.00$
\[ \lambda = 0.63 \]
\[ \phi_1 = \phi_0 - 1.7 \]
\[ \phi_0 = 180.0 \]
\[ \chi = 1.06 \]
\[ \phi_1 = \phi_0 + 1.7 \]
\[ \phi_1 = \theta \]

**BIDIRECTIONAL REFLECTANCE (STER.\(^{-1}\))**

\( \theta_n = 0.00 \quad \phi_n = 99 \quad \phi_m = 180.00 \)
$\lambda = 1.06$
$\phi_i = \phi - 1.0$
$\phi_i = 180.0$

![Graph showing directional reflectance](image-url)
\( \lambda = 3.39 \)
\( \phi_i = \phi_n + 2.0 \)
\( \phi_l = 0.0 \)

**Graph:**
- **Title:** BIDIRECTIONAL REFLECTANCE (STER.-I)
- **Axes:**
  - Y-axis: 10^{-3} to 10^{1}
  - X-axis: 90.0 to 0.0
- **Data Points:**
  - \( \phi_n = 0.0 \)
  - \( \phi_n = 180.00 \)

The graph shows the relationship between bidirectional reflectance and angle in degrees.
\[ \lambda = 3.39 \]
\[ \phi = \phi + 2.0 \]
\[ \phi = 180.0 \]
A02022  604

\[ \lambda = 10.60 \]

\[ \phi_t = \pm 2.5 \]

\[ \phi_i = 0.0 \]

BIDIRECTIONAL REFLECTANCE (STER.\(^{-1}\))

\[ 10^{-2} \]

\[ 10^{0} \]

\[ 10^{2} \]

\[ 10^{4} \]

\[ 10^{6} \]

\[ 10^{8} \]

\[ 10^{10} \]

60. 30. 0. 30. 60. 90.

\[ \phi_i = 0.0 \]

\[ \phi_t = 0.00 \]

\[ \phi_t = 180.00 \]
\( \lambda = 10.60 \)
\( \theta_i = \phi^+ - 2.5 \)
\( \phi_i = 180.0 \)
\[ \lambda = 3.39 \]
\[ \phi_1 = \phi_n^+ = 2.0 \]
\[ \phi_1 = \phi_n^- = 0.0 \]
\[ \lambda = 3.39 \]
\[ \phi_1 = -2.0 \]
\[ \phi_1 = 180.0 \]
\[ \lambda = 10.60 \]
\[ \phi_i = \phi_i + 2.5 \]
\[ \phi_i = 0.0 \]

**BIDIRECTIONAL REFLECTANCE (STER.)**

\[ \varphi_h = 0.00 \]
\[ \varphi_r = 180.00 \]
\( \lambda = 10.60 \)
\( \phi_i = \phi + 2.5 \)
\( \theta_i = 180.0 \)
$\lambda = 0.63$

$\phi_i = \phi_r^\prime - 1.7$

$\phi_i = 180.0$

Bi-directional reflectance (ster$^{-1}$)

$\theta = 0.00$  $\phi_r$ (DEGREES)  $\theta = 180.00$
\[ \lambda = 1.06 \]
\[ \theta_d = 1.7 \]
\[ \phi_i = 0.0 \]

BIODIRECTIONAL REFLECTANCE (STER.\(^{-1}\))

\[ \psi_h = 0.0 \]
\[ \phi_h = 180.00 \]
\[ \lambda = 3.39 \]
\[ \phi_i = \phi_n + 2.0 \]
\[ \phi_i = 0.0 \]

BIDIRECTIONAL REFLECTANCE (STER.\(^{-1}\))

\[ \theta_n = 0.00 \]  \[ \phi_n = 180.00 \]  

(DEGREES)
\( \lambda = 3.39 \)
\( \phi_1 = -2.0 \)
\( \phi_l = 180.0 \)

**Diagram:**

- **Title:** A02022 702
- **Parameters:**
  - \( \lambda = 3.39 \)
  - \( \phi_1 = -2.0 \)
  - \( \phi_l = 180.0 \)
- **Graph:**
  - **Y-axis:** Bi-directional reflectance (ster.⁻¹)
  - **X-axis:** (degrees) from 90° to 0° to 90°
  - **Data Points:** Various reflectance values at different angles.
\[ \lambda = 10.60 \]
\[ \theta_i = 2.5 \]
\[ \phi_i = 180.0 \]
$\lambda = 10.60$
$\theta_i = 2.5$
$\theta_l = 0.0$
\[ \lambda = 10.60 \]
\[ \phi_t = \phi_r + 2.5 \]
\[ \phi_t = 90.0 \]
$A02022\ 602$

$\lambda = 10.60$

$\phi = 2.5$

$\theta = 270.0$

**Bi-directional Reflectance (Ster.)**

- $\phi_1 = 90.00$
- $\phi_2 = 270.00$

Degrees
\[ \gamma = 0.63 \]
\[ \theta_i = 180.0 ^\circ \]

**Bi directional reflectance (ster^-1)**

- \( \theta_n = 0.00 ^\circ \)
- \( \theta_n = 180.00 ^\circ \)

**Graph Details**

- The graph plots bi directional reflectance against the angle of incidence.
\( \lambda = 1.06 \)
\( \psi_i = 0.0 \)
\( \theta_i = 180.0 \)
$\lambda = 10.60$

$\phi_0 = 10.0$

$\phi_1 = 180.0$
\( \lambda = 1.06 \)
\( \theta_i = 20.0 \)
\( \phi_i = 180.0 \)
$\lambda = 3.39$
$\phi_i = 20.0$
$\phi_f = 180.0$
\[ \begin{align*}
\lambda &= 10.60 \\
\phi_i &= 20.0 \\
\phi_f &= 180.0
\end{align*} \]
$\lambda = 1.06$
$\phi_i = 20.0$
$\theta_i = 180.0$

**Bi-directional Reflectance (Ster $^{-1}$)**

- $\phi_h = 90.00$
- $\phi_h = 128$
- $\phi_h = 270.00$
\( \lambda = 10.60 \)

\( \theta_2 = 20.0 \)

\( \theta_1 = 180.0 \)
$\lambda = 0.63$
$
\phi_i = 40.0$

$\phi_i = 180.0$

Bidirectional reflectance (ster$^{-1}$)

$log_{10}$ (reflectance) vs. (degrees)

$\phi_m = 0.00$

$\phi_m = 180.00$
\( \gamma = 1.06 \)
\( \theta = 40.0 \)
\( \phi = 180.0 \)

![Graph of bidirectional reflectance](image_url)
\[ \lambda = 10.60 \]
\[ \theta_i = \text{deg} \]
\[ \phi_i = 160.0 \]

Graph showing bidirectional reflectance (stellar-1) against angle (degrees) with peak values at certain angles.
A01610 101

$\lambda = 0.63$

$\theta_i = 40.0$

$\phi_1 = 180.0$

**Bi-directional Reflectance** (Ster.$^{-1}$)

- $\phi_n = 90.00$
- $\phi_n (\text{degrees})$
- $\phi_n = 270.00$

Graph with three curves representing bi-directional reflectance.
A01610 301

\[ \lambda = 3.39 \]
\[ \phi_1 = 40.0 \]
\[ \phi_2 = 180.0 \]

**BIDIRECTIONAL REFLECTANCE (STER.\(^{-1}\))**

\[ 10^3 \]
\[ 10^2 \]
\[ 10^1 \]
\[ 10^0 \]
\[ 10^{-1} \]
\[ 10^{-2} \]
\[ 10^{-3} \]

![Graph](attachment:image.png)

\[ \theta_n = 90.00 \]
\[ \theta_n = 270.00 \]
\[ \theta_n = 137 \]
\( \lambda = 10.60 \)
\( \phi = 40.0 \)
\( \theta_t = 180.0 \)
\[ \lambda = 0.63 \]
\[ \phi_1 = 60.0 \]
\[ \phi_2 = 180.0 \]
A01610  102

\[
\begin{align*}
\lambda &= 1.06 \\
\phi &= 60.0 \\
\phi_t &= 180.0
\end{align*}
\]
A01610  302

\[ \lambda = 3.39 \]
\[ \phi = 60.0 \]
\[ \phi_1 = 180.0 \]
$\lambda = 10.60$
$\theta_1 = 60.0$
$\phi_1 = 180.0$

Bi-directional reflectance (Ster.$^{-1}$)

$\phi_n = 0.00 \quad \phi_n = 142 \quad \phi_n = 180.00$
A01610  101

$\lambda = 0.63$

$\phi_1 = 60.0$

$\phi_2 = 180.0$

BIDIRECTIONAL REFLECTANCE (STER. -1)

$\theta_i = 90.00 \quad \theta_m \quad (DEGREES) \quad \theta_r = 270.00$

90.  60.  30.  0.  30.  60.  90.
\[ \lambda = 1.06 \]
\[ \theta_i = 60.0 \]
\[ \phi_i = 180.0 \]
\( \lambda = 3.39 \)
\( \phi_1 = 60.0 \)
\( \phi_2 = 180.0 \)

BIDIRECTIONAL REFLECTANCE (STER.\(^{-1}\))

\( \theta_m = 90.00 \)
\( \theta_m = 270.00 \)
$A_01610 \quad 201$

$\lambda = 10.60$

$\psi_i = 60.0$

$\phi_i = 180.0$

BIODIRECTIONAL REFLECTANCE (STER.$^{-1}$)

$\phi$ (DEGREES) $\theta$ $= 90.00$ $\phi$ $= 270.00$
\[ \lambda = 3.39 \]
\[ \theta_1 = 0 \]
\[ \phi_1 = 180.0 \]
\[ \theta = 10.60 \]
\[ \phi = 0.0 \]
\[ \gamma = 180.0 \]
\( \chi = 3.39 \)
\( \phi_i = 20.0 \)
\( \phi_l = 180.0 \)

**Graph: Bidirectional Reflectance (STER.\(^{-1}\))**

- **Sources:**
  - \( \phi_n = 0.0 \)
  - \( \phi_n = 180.0 \)
\[ \lambda = 10.60 \]
\[ \phi_1 = 20.0 \]
\[ \phi_2 = 180.0 \]
H01610 203

\[ \lambda = 10.60 \]
\[ \Phi_1 = 40.0 \]
\[ \Phi_2 = 180.0 \]

**Bidirectional Reflectance (Ster.-1)**

\[ \phi_n = 0.00 \]
\[ \phi_n = 180.00 \]
\( \lambda = 3.39 \)

\( \phi_\| = 40.0 \)

\( \phi_\perp = 180.0 \)

\( \phi_{\text{m}} = 90.00 \) (DEGREES)

\( \phi_{\text{m}} = 270.00 \)
$\chi = 0.63$

$\phi_j = 180.0$
A01610 102

λ = 1.06
θ_i = 0.0
θ_t = 180.0

BI DIRECTIONAL REFLECTANCE (STER.^-1)

10^1

10^2

10^3

10^4

90.0 60.0 30.0 0.0 30.0 60.0 90.0

θ_h = 0.00 θ_i = 180.00
A01610  204

$\theta = 10.60$

$\phi = 0$

$\psi = 180.0$

BIDIRECTIONAL REFLECTANCE (STER.$^{-1}$)

10$^{-2}$

10$^{-1}$

10$^{0}$

10$^{1}$

90.  60.  30.  0.  30.  60.  90.

$\theta_{in} = 0.00$  $\theta_{out} = 180.00$
A01610 101

\[ \lambda = 0.63 \]
\[ \phi = 20.0 \]
\[ \phi_2 = 180.0 \]

BIDIRECTIONAL REFLECTANCE (STER.\(^{-1}\))

\[ \theta_n = 0.00 \quad \phi_{163} = \phi_n = 180.00 \]
\[ \lambda = 1.06 \]
\[ \phi_t = 20.0 \]
\[ \theta_t = 180.0 \]
λ = 3.39
θ = 20.0
φ ≈ 180.0
\( \lambda = 10.60 \)
\( \phi_i = 20.0 \)
\( \theta_i = 180.0 \)
\[ \lambda = 0.63 \]
\[ \phi_1 = 20.0 \]
\[ \phi_2 = 180.0 \]
A01610  302

\[ \lambda = 3.39 \]
\[ \phi_1 = 20.0 \]
\[ \phi_1 = 180.0 \]
$\lambda = 0.63$

$\phi_1 = 40.0$

$\phi_1 = 180.0$
$\lambda = 3.39$
$\phi_i = 40.0$
$\phi_f = 180.0$

BIDIRECTIONAL REFLECTANCE (STER.-1)

$\theta_h = 0.00$ $\theta_j = 172$
$\theta_h = 180.00$
\[ \lambda = 10.60 \]
\[ \phi_i = 40.0 \]
\[ \phi_f = 180.0 \]
\[ \lambda = 0.63 \]

\[ \theta_i = 40.0 \]

\[ \phi_i = 180.0 \]
\[ \begin{align*} 
\lambda & = 1.06 \\
\phi_1 & = 40.0 \\
\Theta & = 0.0 
\end{align*} \]
A01610  302

\( \lambda = 3.39 \)
\( \phi_i = 40.0 \)
\( \phi_j = 180.0 \)

BIDIRECTIONAL REFLECTANCE (STER. -1)

10^1
10^0
10^(-1)
10^(-2)
10^(-3)

90.  60.  30.  0.  30.  60.  90.

\( \phi_a = 90.00 \quad \phi_a = 176 \quad \phi_a = 270.00 \)
\( \chi = 0.63 \)
\( \phi_2 = 60.0 \)
\( \phi_1 = 180.0 \)
\( \lambda = 1.06 \)
\( \theta_i = 60.0 \)
\( \theta_f = 180.0 \)
\[
\begin{align*}
\lambda &= 3.39 \\
\phi_i &= 60.0 \\
\phi_f &= 180.0
\end{align*}
\]
A01610  204

\( \lambda = 10.60 \)

\( \theta_I = 60.0 \)

\( \phi_I = 180.0 \)
\( \chi = 0.63 \)
\( \phi_i = 60.0 \)
\( \phi_f = 180.0 \)

Diagram showing bi-directional reflectance with angles in degrees.
$\lambda = 0.63$
$\phi = 0$
$\theta = 180.0$
\[ \lambda = 1.06 \]
\[ \phi = 0.0 \]
\[ \phi_1 = 180.0 \]
A02022  602

λ = 10.60
Θ = 0.0
Θ = 180.0
\[ \lambda = 0.63 \]
\[ \phi_1 = 0.0 \]
\[ \phi_1 = 180.0 \]
$\lambda = 1.06$

$\phi_i = 0$

$\phi_s = 180.0$

**BIORECTIONAL REFLECTANCE (STER. $^{-1}$)**

$\phi_i = 90.00$

$\phi_s = 270.00$

$\phi_s = 189$

$\phi_i = 90.00$
\[ \lambda = 0.63 \]
\[ \phi_t = 20.0 \]
\[ \phi_i = 180.0 \]
\[ \lambda = 3.39 \]
\[ \theta_I = 20.0 \]
\[ \theta_T = 180.0 \]
\( \lambda = 10.60 \)
\( \phi_t = 20.0 \)
\( \phi_i = 180.0 \)
A02022 201

\[ \lambda = 1.06 \]
\[ \phi_1 = 20.0 \]
\[ \phi_1 = 180.0 \]

BIDIRECTIONAL REFLECTANCE (STER.-1)

\( \phi_n, \theta_n \) (DEGREES)

\( \phi_n = 90.00 \quad \theta_n = 195 \quad \phi_n = 270.00 \)
\[ \lambda = 3.39 \]
\[ \phi_i = 20.0 \]
\[ \phi_i = 180.0 \]
\( \lambda = 10.60 \)
\( \phi_z = 20.0 \)
\( \phi_t = 180.0 \)
\[ \beta = 0.63 \]
\[ \gamma = 40.0 \]
\[ \phi = 180.0 \]
$$\lambda = 3.39$$
$$\phi_1 = 40.0$$
$$\phi_1 = 180.0$$
HUCUC CUC

\[ \lambda = 0.63 \]
\[ \theta_i = 40.0 \]
\[ \phi_i = 180.0 \]

BIODIRECTIONAL REFLECTANCE (STER-1)

90. 60. 30. 0. 30. 60. 90.

\[ \theta_n = 90.00 \]
\[ \phi_n = 270.00 \]
A02022  201

\[ \lambda = 1.06 \]
\[ \phi_1 = 40.0 \]
\[ \phi_2 = 180.0 \]

**Diagram:**

- Title: Bi-directional Reflectance (Ster.-1)
- Axes:
  - Y-axis: Bi-directional Reflectance (Ster.-1)
  - X-axis: Angle (Degrees)

- Key points:
  - \( \phi_n = 80.00 \)
  - \( \phi_n = 270.00 \)
A02022  701

\( \lambda = 3.39 \)

\( \phi_1 = 40.0 \)

\( \phi_1 = 180.0 \)
$\chi = 10.60$
$\phi_i = 40.0$
$\phi_f = 180.0$

Bidirectional reflectance (ster. -1)

$\theta_{\text{in}} = 90.00$ $\theta_{\text{out}}$ (degrees) $\theta_{\text{out}} = 270.00$
$\lambda = 3.39$
$\phi_1 = 60.0$
$\phi_2 = 180.0$

BIDIRECTIONAL REFLECTANCE (STER.$^{-1}$)}
A02022  602

$\lambda = 10.60$

$\varphi_t = 60.0$

$\varphi_r = 180.0$

BIDIRECTIONAL REFLECTANCE (STER.)

$\theta_0 = 0.00$  $\theta_209 = 209.00$  $\theta_180 = 180.00$

$\phi$ (DEGREES)
\( \lambda = 0.63 \)
\( \phi_i = 60.0 \)
\( \phi_f = 180.0 \)

**BIDIRECTIONAL REFLECTANCE (STER. -1)**

\( \phi_r = 80.00 \) \( \phi_r = 270.00 \)
\[ \lambda = 1.06 \]
\[ \phi = 60.0 \]
\[ \phi_i = 180.0 \]

**Bi-directional Reflectance (STER.\(^{-1}\))**

- \( \Theta_{\text{m}} = 90.00 \)
- \( \Theta_{\text{m}} = 270.00 \)

Graph showing bi-directional reflectance as a function of the angle of incidence. The graph is plotted on a logarithmic scale for both axes.
\[ \lambda = 3.39 \]
\[ \phi = 60.0 \]
\[ \phi_1 = 180.0 \]

Diagram with bidirectional reflectance in steradians.
A02022  604

\[ \lambda = 10.60 \]
\[ \phi_i = 60.0 \]
\[ \phi_r = 180.0 \]

**Bidirectional Reflectance (ster.\(^{-1}\))**

- \( \phi_h = 90.00 \) (Degrees)
- \( \phi_i = 213 \)
- \( \phi_r = 270.00 \)
$\lambda = 3.39$
$\phi_1 = 0.0$
$\phi_1 = 180.0$

**BIDIRECTIONAL REFLECTANCE (STER.$^{-1}$)**

$\phi_m = 0.00$  $\phi_m = 180.00$

(degrees)
\[ \lambda = 3.39 \]
\[ \phi_1 = 20.0 \]
\[ \phi_1 = 180.0 \]
A02022  703

\[ \lambda = 3.39 \]
\[ \phi_1 = 20.0 \]
\[ \phi_i = 180.0 \]

BIDIRECTIONAL REFLECTANCE (STER.)

\( \phi_n = 90.00 \quad \phi_n \) (DEGREES) \[ \phi_n = 270.00 \]
\[ \lambda = 3.39 \]
\[ \phi_i = 40.0 \]
\[ \phi_f = 180.0 \]
\[ \lambda = 10.60 \]
\[ \phi_t = 40.0 \]
\[ \phi_r = 180.0 \]
$\lambda = 3.39$
$\phi_1 = 40.0$
$\phi_2 = 180.0$
\( \lambda = 3.39 \)
\( \phi_l = 60.0 \)
\( \phi_r = 180.0 \)
\( \lambda = 10.60 \)
\( \phi_i = 60.0 \)
\( \phi_f = 180.0 \)
\[ \lambda = 3.39 \]
\[ \phi_1 = 60.0 \]
\[ \phi_4 = 180.0 \]
\( \lambda = 10.60 \)
\( \phi_i = 60.0 \)
\( \phi_r = 180.0 \)
\[ \lambda = 0.63 \]
\[ \phi_i = 180.0 \]
MUCUC 2U1

\[ \lambda = 1.06 \]

\[ \mu = 0 \]

\[ \phi_i = 180.0 \]

Diagram showing bidirectional reflectance (ster.-1) versus angle (degrees) for different conditions.
\[ \lambda = 10.60 \]
\[ \phi_t = 0 \]
\[ \phi_s = 180.0 \]
A02022  201

$\lambda = 1.06$

$\phi_i = 0$

$\phi_f = 180.0$

**Bidirectional Reflectance (Ster.-1)**

$\phi_h = 90.00$  $\phi_h = 233$  $\phi_h = 270.00$
\[ \lambda = 0.63 \]
\[ \phi_1 = 20.0 \]
\[ \phi_2 = 180.0 \]
\( \lambda = 10.60 \)

\( \theta_i = 20.0 \)

\( \phi_i = 180.0 \)
A02022 202

$\gamma = 0.63$

$\phi = 20.0$

$\theta = 180.0$

Bi-directional reflectance (ster.$^{-1}$)

$\phi_m = 90.00, \phi = 238, \theta_m = 270.00$

Degrees
\( \lambda = 10.60 \)
\( \phi_t = 20.0 \)
\( \phi_i = 180.0 \)
$\lambda = 1.06$
$\theta = 40.0$
$\phi = 180.0$
A02022 701

\( \lambda = 3.39 \)

\( \phi = 40.0 \)

\( \phi_1 = 180.0 \)

BIDIRECTIONAL REFLECTANCE (STER^-1)

\( \theta_\text{in} = .00 \quad \theta_\text{out} \quad 244 \quad \theta_\text{out} = 180.00 \)
A02022  202

\[ \lambda = 0.63 \]
\[ \phi = 40.0 \]
\[ \phi_1 = 180.0 \]

Bidirectional Reflectance (ster^-1)

\[ 10^{-2} \]
\[ 10^{-1} \]
\[ 10^0 \]

\( \phi_m = 90.00 \)  \( \phi_m = 246 \)  \( \phi_m = 270.00 \)

90.  60.  30.  0.  30.  60.  90.
\[ \lambda = 1.06 \]
\[ \phi_2 = 40.0 \]
\[ \phi_3 = 180.0 \]
$\lambda = 3.39$
$\phi_\theta = 40.0$
$\phi_i = 180.0$
\( \lambda = 1.06 \)
\( \phi = 60.0 \)
\( \theta = 180.0 \)

The graph shows the bi-directional reflectance (ster. -1) as a function of \( \theta \) (degrees). The curves indicate the reflectance for different angles, with \( \phi_m = 0.00 \) and \( \phi_m = 180.00 \).
\( \lambda = 3.39 \)

\( \phi_1 = 60.0 \)

\( \phi_2 = 180.0 \)
$\lambda = 10.60$
$\phi_t = 60.0$
$\phi_f = 180.0$
$\chi = 1.06$

$\phi = 60.0$

$\phi_1 = 180.0$
$\lambda = 3.39$

$\phi_i = 60.0$

$\phi_f = 180.0$

BIODIRECTIONAL REFLECTANCE (STER. $^{-1}$)

$\theta_m = 80.00$  $\phi_m = 270.00$
A02023  101

$\lambda = 1.06$

$\phi = 180.0$

![](image)

**RADIATION REFLECTANCE (STER.$^{-1}$)**

$\phi_n = 90.00 
\phi_m = 260 
\phi_r = 270.00$
\( \lambda = 1.06 \)
\( \theta_i = 20.0 \)
\( \theta_f = 160.0 \)
\[ \lambda = 3.39 \]
\[ \phi_r = 20.0 \]
\[ \phi_t = 180.0 \]
A02023  602

\( \lambda = 10.60 \)
\( \sigma_1 = 20.0 \)
\( \sigma_t = 180.0 \)
$\lambda = 0.63$
$\theta_i = 20.0$
$\phi_i = 180.0$

**BIDIRECTIONAL REFLECTANCE (STER. 1)**

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$\phi_h$: 0.00 (Degree)  $\phi_h$: 170.00
$\lambda = 1.06$

$\theta = 20.0$

$\phi = 180.0$
\( \lambda = 3.39 \)
\( \phi_1 = 20.0 \)
\( \phi_2 = 180.0 \)
A02023  604

λ = 10.60
φ = 20.0
θ₀ = 180.0

BIDIRECTIONAL REFLECTANCE (STER⁻¹)

90.  60.  30.  0.  30.  60.  90.

θ₀ = 90.00  267  φ = 270.00
\[ \lambda = 3.39 \]
\[ \theta_1 = 40.0 \]
\[ \phi_1 = 180.0 \]
\[ \lambda = 10.60 \]
\[ \phi_t = 40.0 \]
\[ \phi_f = 180.0 \]
$\lambda = 63$
$\phi_t = 40.0$
$\phi_i = 180.0$

Bidirectional Reflectance (Ster.-1)

$\phi_m = 90.00 \quad \phi_m$ (Degrees) $\quad \phi_m = 270.00$
$A_02023 \ 101$

$\lambda = 1.06$

$\phi_1 = 40.0$

$\phi_2 = 180.0$

BIDIRECTIONAL REFLECTANCE (STER.$^{-1}$)

$\theta_R = 90.00 \ \theta_A (DEGREES) \ \theta_A = 270.00$
\[ \lambda = 3.39 \]
\[ \theta_1 = 40.0 \]
\[ \phi_1 = 180.0 \]
\( \lambda = 1.06 \)
\( \phi_1 = 60.0 \)
\( \phi_1 = 180.0 \)

**Bidirectional Reflectance (Ster. -1)**

\[ \theta_R = 0.00 \quad \theta_R (\text{DEGREES}) \]
\[ \phi = 275 \]
\[ \phi_R = 180.00 \]
\[ \lambda = 10.50 \]
\[ \Phi_I = 60.0 \]
\[ \Phi_f = 180.0 \]
\( \chi = 0.63 \)
\( \phi_t = 60.0 \)
\( \phi_t = 180.0 \)
A02023  701

\[ \lambda = 3.39 \]
\[ \Phi_1 = 60.0 \]
\[ \Phi_1 = 180.0 \]
$\lambda = 10.60$
$\theta_i = 60.0$
$\phi_i = 180.0$

Bidirectional Reflectance (Ster.)

$\theta_h = 90.00$  $\phi_h$ (DEGREGS)  $\theta_h = 270.00$
\[ \lambda = 3.39 \]
\[ \phi_e = 0 \]
\[ \phi_i = 180.0 \]
\( \lambda = 10.60 \)
\( \phi_t = 0.0 \)
\( \phi_f = 180.0 \)
\( \lambda = 3.39 \)

\( \phi_1 = 20.0 \)

\( \phi_2 = 180.0 \)
$\lambda = 10.60$

$\phi_i = 20.0$

$\phi_f = 180.0$
\( \lambda = 3.39 \)
\( \Phi_1 = 20.0 \)
\( \Phi_1 = 180.0 \)

\[ \begin{align*}
\phi_n & = 90.00 \\
\phi_r (\text{DEGREES}) & = 286 \\
\phi_n & = 270.00
\end{align*} \]
\( \lambda = 10.60 \)
\( \theta_i = 20.0 \)
\( \theta_f = 180.0 \)
\( \lambda = 3.39 \)
\( \phi_1 = 40.0 \)
\( \phi_1 = 180.0 \)
\( A02023 \quad 603 \)

\( \lambda = 10.60 \)
\( \phi_r = 40.0 \)
\( \phi_t = 180.0 \)

**BIDIRECTIONAL REFLECTANCE (STER. 1)**

\[ \phi_n = 90.00 \quad \phi_n = 270.00 \]
$\lambda = 3.39$
$\phi_1 = 60.0$
$\phi_1 = 180.0$
$\lambda = 10.60$
$\Phi_r = 60.0$
$\phi_t = 180.0$

Bi-directional Reflectance (Ster.$^{-1}$)

$\phi_h = 0.00$  $\phi_h (\text{degrees})$  $\phi_h = 180.00$
\( \lambda = 3.39 \)
\( \theta_1 = 60.0 \)
\( \phi_1 = 180.0 \)

**Diagram:**

- **Title:** BIDIRECTIONAL REFLECTANCE (STER. -1)
- **Axes:**
  - Y-axis: 10^-3 to 10^-1
  - X-axis: 90.0 to 90.0 (in degrees)
- **Data Points:** Plotted values indicating reflectance measurements.

**Notes:**

- \( \phi_R = 90.00 \) (Degrees) on the graph.
- \( \phi_R = 270.00 \) (Degrees) on the graph.
\[ \lambda = 10.60 \]
\[ \theta_i = 60.0 \]
\[ \theta_f = 180.0 \]
$\lambda = 1.06$

$\phi_i = 180.0$

$\phi_i = 0.0$

$\phi_i = 90.0$

$\phi_i = 60.0$

$\phi_i = 30.0$

$\phi_i = 0.0$

$\phi_i = 30.0$

$\phi_i = 60.0$

$\phi_i = 90.0$

$\phi_i = 297.0$

$\phi_i = 180.0$

BIDIRECTIONAL REFLECTANCE (STER.-1)

\begin{align*}
\text{BIDIRECTIONAL REFLECTANCE} & \propto \frac{1}{\sin \phi_i} \\
\text{BIDIRECTIONAL REFLECTANCE} & \propto \frac{1}{\theta_i} \\
\text{BIDIRECTIONAL REFLECTANCE} & \propto \frac{1}{\sin \theta_i} \\
\text{BIDIRECTIONAL REFLECTANCE} & \propto \frac{1}{\cos \phi_i} \\
\end{align*}
A02023 701

\[ \lambda = 3.39 \]
\[ \phi_1 = 0 \]
\[ \phi_1 = 180.0 \]

**Bidirectional Reflectance (Ster.-1)**

- \( \phi_1 \) values: 0°, 60°, 30°, 0°, 30°, 60°, 90°

- \( \phi_\text{M} \) values: 0.00, 80.00
\( \lambda = 1.06 \)
\( \phi_1 = 0 \)
\( \phi_2 = 180.0 \)

**Bi-directional Reflectance (Ster^-1)**

- \( \phi_H = 90.00 \)
- \( \phi_H = 300 \)
- \( \phi_H = 270.00 \)
A02023  501

\[ \lambda = 0.63 \]
\[ \phi_i = 20.0 \]
\[ \phi_r = 180.0 \]
A02023 101

λ = 1.06
ψ = 20.0
ϕ_i = 180.0

BIDIRECTIONAL REFLECTANCE (STER.-1)

θ_m = 0.00  ψ_m = 180.00

(degrees)
\( \lambda = 3.39 \)

\( \phi_x = 20.0 \)

\( \phi_y = 180.0 \)
\( \lambda = 10.60 \)
\( \phi = 20.0 \)
\( \phi = 180.0 \)

![Graph showing bi-directional reflectance (steradian^-1) vs. \( \theta_h \) (degrees).](image)
\( \gamma = 0.63 \)
\( \theta = 20.0 \)
\( \theta_r = 180.0 \)
\[ \lambda = 3.39 \]
\[ \phi_1 = 20.0 \]
\[ \phi_1 = 180.0 \]
$\lambda = 0.63$

$\theta_f = 40.0$

$\phi_f = 180.0$

The graph shows the bidirectional reflectance (ster.$^{-1}$) for various angles $\theta$ and $\phi$.
\[ \phi_s = 1.06 \]
\[ \theta = 40.0 \]
\[ \phi_d = 180.0 \]
\( \lambda = 3.39 \)
\( \Phi_1 = 40.0 \)
\( \Phi_1 = 180.0 \)
\[ \lambda = 10.60 \]
\[ \phi_t = 40.0 \]
\[ \phi_t = 180.0 \]
A02023      501

$\chi = 0.63$

$\phi_1 = 40.0$

$\phi_1 = 180.0$

BI DIREC T I ONAL R E F L E C T A N C E  (S T E R. )

$\theta_h = 90.00 \quad \phi_h = 270.00$
\( \chi = 1.06 \)
\( \phi = 40.0 \)
\( \phi_1 = 180.0 \)
A02023 702

\[ \lambda = 3.39 \]
\[ \phi_1 = 40.0 \]
\[ \phi_2 = 180.0 \]

BIDIRECTIONAL REFLECTANCE (STER.-1)

[Graph showing data points and axes with values]
\( \lambda = 10.60 \)
\( \phi_r = 40.0 \)
\( \phi_t = 180.0 \)
\[ \lambda = 0.63 \]
\[ \phi_r = 60.0 \]
\[ \phi_t = 180.0 \]
\( \gamma = 1.06 \)

\( \phi = 60.0 \)

\( \phi' = 180.0 \)

**Graph: Bi-directional Reflectance (Ster. -1)**

Axes:
- Y-axis: Bi-directional Reflectance (Ster. -1)
- X-axis: \( \phi_n \) (Degrees)

Points:
- \( \phi_n = 0.00 \)
- \( \phi_n = 180.00 \)
\( \lambda = 3.39 \)
\( \phi_1 = 60.0 \)
\( \phi_2 = 180.0 \)

![Graph of Bi-directional Reflectance (Ster. -1)](image)
$\lambda = 10.60$
$\phi_t = 60.0$
$\phi_i = 180.0$

**Bidirectional Reflectance (Ster.)**

- **Axes:**
  - Y-axis: $10^{-1}$ to $10^{0}$
  - X-axis: 90.0 to 90.0

- **Legend:**
  - $\phi_i = 0.0$ to 320
  - $\phi_i = 180.00$
R02023  501

\[ \lambda = 0.63 \]
\[ \varphi_t = 60.0 \]
\[ \varphi_i = 180.0 \]
\( \lambda = 3.39 \)
\( \phi_1 = 60.0 \)
\( \phi_i = 180.0 \)

\( \phi_f = 90.00 \)  \( \phi_m = 270.00 \)
\( \lambda = 10.60 \)
\( \theta_i = 60.0 \)
\( \phi_i = 180.0 \)

**BIORECTIONAL REFLECTION (STER.-1)**

\( \phi_n = 90.00 \)  \( \phi_n \) (DEGREES)  \( \phi_A = 270.00 \)