The Measurement of the Directional Hemispherical Reflectance from Spectralon

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Abstract

The directional hemispheric reflectance is measured for Spectralon, the material chosen for on-board radiometric calibration of the Multiangle Imaging SpectroRadiometer (M ISR), at laser wavelengths of 442, 632.8 and 859.9 nm. With P - and S - polarized incident light and for an angle of incidence of450, the bidirectional reflectance function was measured over a polar angle range of 10 through **850** and a range of azimuthal angles of 00 through 1800. The resultant hemispheric reflectance is found to be 1.00 ± 0.01 at 442, 0.953 ± 0.01 at 632.8 nm, and 0.956 ± 0.01 at 859.9 nm. The experimental methodology and the data analysis arc presented together with a full discussion of the primary experimental errors.

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1. Introduction

The utilization of On-Board Calibrator (OBC) systems on satellite remote sensors necessitates the characterization of the optical reflectance properties of candidate materials for use as the diffuse reflectance standard. Spectralon, a polytetrafluoroethy lene type material made by Labsphere Inc. is one such candidate material. Indeed, Spectralon has been selected for use on the Moderate Resolution Imaging Spectrometer Nadir / Tilt (MODIS- N/T) and the Multi-angle Imaging SpectroRadiometer (MISR) instruments as the diffuse reflectance standard. The MODIS and MISR instruments will be lauched aboard the NASA EOS (Earth Observing System) AM-1 Spacecraft in 1998.

For the radiometric measurements from Earth-orbiting sensors such as MODIS- N/T and MISR to be most useful in quantifying the radiation transfer properties of the Earth surface and the atmosphere, all the competing processes must be described and quantified. This can best be achieved if the individual measurements are made in the absolute sense.

Absolute values of reflectance are usually difficult to achieve because the solid angles and flux measurements are difficult to define with a high degreee of precision. The laboratory offers the best opportunity to make these measurements due to the control which may be provided. Thus the procedure to be adopted is to calibrate absolutely the reflectance standards in the laboratory and to usc these standards periodically to calibrate the active measurements being made in the environment(').

Four optical characteristics of reflectance standards for OBC's for Earth orbiting radiometric satellites must be measured: The bidirectional reflectance distribution function (BRDF), the bi-directional reflectance factor (BRF), depolarization of reflected light and the directional hemispheric reflectance. These four characterist ics must bc measured at the spectral bandpasses of the radiometer and for the polarization state of the radiation that may be incident. The bidirectional reflectance factor (BRF) is defined as a dimensionless ratio of the bidirectional reflectance distribution function (BRDF) of the material to the BRDF of a perfect Lambertian reflector, which is $1/\pi$ sr-' .

To measure these optical characteristics of the reflectance standards a computer controlled experiment with digital data acquition was developed at the Jet Propulsion Laboratory '2). This facility was used to characterize the BRF of the reflectance standards '3) as well as the depolarization of the reflected light(4).

Since there are no known perfect Lambertian reflectors to be used as a transfer material, the approach presented here is to perform an absolute calibration of the SpectraIon calibration panels to be used in the MISR experiment. The theory will be presented to establish the background to the actual experimental details which will be described in Section 3.

2. **Theory**

The primary reflectance property of the Spectralon to be measured is the BRDF, which is defined to bc the ratio of the reflected radiance to the incident irradiance. Specifically,

$$f(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi) = \frac{dL(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi)}{dE(\theta_i, \phi_i : \lambda, \xi)} \qquad [sr^{-1}]$$

where O, , ϕ_i , θ_r , ϕ_r are the usual spherical coordinates referenced to the surface normal and a reference line on the surface and λ, ξ are respectively the wavelength and polarization specification employed ‘5).

The BRDF is a derivative relating two different radiance measurements which are ray associated quantities that depend on a point in space and on the ray direction through that point. The radiance at a point on a surface in the direction of a ray through that point is defined as the radiant flux or power per unit projected area perpendicular to the ray at the point and unit solid-angle in the direction of the ray at the point [(6)]. This is expressed as

$$L\ (\theta_i\ ,\ \phi_i\ :\ \theta_r\ ,\ \phi_r\ :\ \lambda\ ,\ \xi)\ =\ \frac{d^2\phi_r}{dA_r\ \cos\theta\ d\omega}$$

where $d^2\phi_r$ is the radiant flux from the surface element dA, and within the solid angle dω, dA, cosθ is the element of projected area perpendicular to the ray direction.

The irradiance dE (θ_i , ϕ_i , λ, ξ) = d@, / dA, , where the radiant flux is ncident upon the unit area of the surface intercepting the radiation along the ray from the source to the point of incidence.

‘l’he BRDF as defined with respect to the radiant flux,

$$f_r\ (\theta_i\ ,\ \phi_i\ :\ \theta_r\ ,\ \phi_r\ :\ \lambda,\ \xi)\ =\ \frac{\dfrac{d^2\phi_r}{dA_r\ \cos\theta_r\ d\omega_r}}{\dfrac{d\phi_i}{dA_i}}$$

For the special case where the total area illuminated is included in the field of view of the detector used to measure the radiant flux reflected from the material then: $dA_i = dA$, . Thus,

$$f_r(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi) = \frac{d^2\phi_r}{d\phi_i \cos\theta_r \, d\omega_r} .$$

In the laboratory measurements, the radiant flux is converted to electrical signals through the use of photodetectors where the optical apertures are finite and the BRDF is approximated as a finite difference function over a selected number of points in the coordinate system. This corresponds to:

$$f_r(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi) = \frac{S_r(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi)}{S_i(\theta_i, \phi_i : \lambda, \xi) \cos\theta_r \, d\omega_r}$$

where $S_r(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi)$ is the electronic signal from the reflection detector, and S, $(\theta_i, \phi_i : \lambda, \xi)$ is the electronic signal from the incident flux detector. This is measured by evaluation of S, $(\pi/2, \pi : \lambda, \xi)$.

The *absolute* calibration of the BRDF requires that the directional hemispheric reflectance be evaluated experimentally. The directional hemispheric reflectance is given by:

$$R(\theta_i, \phi_i : 2\pi : \lambda, \xi) = \int_{2\pi} f_r(\theta_i, \phi_i : \theta_r, \phi_r : \lambda, \xi) \, d\Omega_r$$

where the integral is evaluated over the hemisphere and $d\Omega_r$ is the projected solid angle, $\cos\theta_r \sin\theta_r \, d\theta_r \, d\Phi$,. The domain of the integration is $O \le \theta \le \pi/2$, $O \le \Phi \le 2\pi$.

3. Experiment

The four-axis precision reflectance characterization facility, constructed specifically for the characterization of the hi-directional reflectance properties of the panels planned for use as in-flight calibrators on the MISR instrument, was used for the hemispheric reflectance measurements[(2)]. The incident linearly polarized radiation is provided at three laser wavelengths: 442 nm, 632.8 nm and

859.9 nm. Each beam is conditioned to be collimated when incident on the Spectralon. The illuminated area of the panel is viewed using a silicon photodetector which revolves around the panel (360 0, on a 30 cm boom extending from a common rotational axis. This detector signal is ratioed with that from a reference detector which monitors the incident light in order to minimize the effect of amplitude instabilities in the laser sources.

The radiance reflected from the surface is represented by the digitized reflectance detector response [3] which has a reproducible precision index of about 0.2°/0. These data were collected at 100 intervals in the polar angle, θ, over the azimuthal angle, ϕ, taken at 10° intrvals. This 9 x 19 data grid over one-half of the hemisphere was to one side of the plane of incidence which is defined by the surface normal and the incident radiation. These measurements of reflected radiance must be compared to the incident irradiance in absolute value in order to obtain the directional hemispheric reflectance. This is acomplished by calibrating the incident energy and the corresponding voltage using the *same* detector assembly as used in measuring the reflected radiance. This technique required no adjustment of the system electronics to obtain a proportional voltage in the usual data range and was achieved by reducing the energy on the detector from the incident beam by using accurately calibrated neutral density filters at each of the three wavelengths.

The calibration of signals is given by: $S_i(\pi/2, \pi; \xi) = S_i^0 10^{OD}$ where S, $(\pi/2{:}\pi, \lambda, \xi)$ is the voltage representative of the incident irradiance, SO, is the voltage recorded as the incident beam passes the calibrated neutral density filter and is incident on the reflectance detector. Care is taken to maintain proper alignment and aperturing of the reflectance detector so that the signal calibration has a precision that is limited only by the uncertainty in the optical density value of each of the filters. As a further check on the absolute calibration, the optical density of each filter was measured over the signal dynamic range of the laboratory electronics. These values were found to agreee to within 0.7%. This technique was used to calibrate the 859.9 nm optical density.

4. **Results**

The data points of reflectance over the half-hemisphere were put into a grid in 10° intervals over,

$0° < \theta < 80°$ **and** $0° < \phi < 180°$ **and** the grid values at $\theta = 90°$ were set to zero on theoretical grounds. This is represented by the two dimensional grid shown in Fig. 1. Using modified software for a cubic spline interpolation the grid of data was increased to a 5 x 5 degree grid [7] and the data were then integrated using a two dimensional Simpson's integration[8,9]. These integrations were checked using an independent technique and found to agree at the 0.1 % level[10]. The results of the directional hemispherical reflectance for the SpectraIon test pieces are shown in Table 1.

These results show that the average absolute directional hemispherical reflectance is 0.966 ± 0.04 for the SpectraIon at visible and near infrared wavelengths. The absolute directional hemispheric reflectance for a Lambertian material would be 1.0; thus showing that Spectralon has a near-Lambertian property. While there are some differences in the entries in the table, these are within the range due to experimental fluctuations and should not be considered as significant, The error analysis for these experiments are part of the discussion.

S. **Discussion**

The details of the care taken in obtaining the data used as the fundamental points on which to base the integration are presented in the companion report '3). I lowever the following is presented in order to obtain a precision index for the directional hemispheric reflectance. The quantities to consider appear in the expression:

$$R(\theta_i, \phi_i : 2\pi : \lambda, \xi) - \frac{1}{S_i(\pi/2, \pi : \lambda, \xi)\, \Omega_D} \int_{2\Pi} S_r(\theta_i, \phi_i : 0, \phi_r : \lambda, \xi) \sin\theta \, d\epsilon$$

where Ω_D is the solid angle subtended by the detector (2 O). This expression is treated using the principles of error propagation [11]

$$\frac{dR}{R} = \frac{'St}{S_i} + \frac{d\Omega_D}{\Omega_D} + \frac{dI}{I}$$

where each term is the relative error for the factor contributing to the error, S, is the incident irradiance and I is the two dimensional integral.

Each of the relative errors are evaluated based on actual measurements or estimates of upper bounds. The incident energy S_i, has its greatest attributable error in the calibration of the neutral density filters which are given to three significant figures in the mantissa. This should mean that the uncertainty in the calibration is 0.002. The solid angle subtended, Ω_D, can be calculated from measurements of the aperture of the detector and the distance from the surface to the aperture. Using an estimated error in the aperture diameter of 0.01 cm and an error of 2.0 mm in the distance to surface, the relative error in Ω_D would be 0.034. The relative error due to data fluctuations in the integral if they are taken to be systematic - a maximizing point of view, would contribute errors of 0.004 based on the standard deviations of the data points. However another technique was used to estimate the data grid fluctuations. The original data points included measurements at θ = 850 which were compared to these interpolated values on the 50 grid. These were found to typically have a variation of+ 0.005 which translates into a relative error in the integral of+ 0.002. Summing these contributions gives the maximum relative error in the directional hemispherical reflectance of 0.04 (4. 0%).

6. Conclusions

In conclusion, the directional hemispheric reflectance for Spectralon at laser wavelengths of 442, 632.8 and 859.9 nm has been measured. With P - and S - polarized incident light and for an angle of incidence of450, the bidirectional reflectance function was measured over a polar angle range of 10 through 850 and a range of azimuthal angles of 0° through 1800 with the resultant hemispheric reflectance determined to be 1.00+ 0.01 at 442 nm , 0.946+ 0.01 at 632.8 nm, and 0.956 ± 0.01 at a wavelength of 859.9 nm. These values compare very well with the average value of 0.99 obtained for pressed polytetrafluroroethylene powder by other laboratories[12]. Further, the anal ysis indicates that the accumulated precision index for the directional hemispheric reflectance is ± 0.04 and is controlled by the precision in determining the detector solid angle.

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Wavelength (nm)	Hemispheric Reflectance
442 (P)	**1.00**
442 (S)	1.01
632.8 (P)	0.950
632.8 (S)	0.956
859.9 (P)	**0.953**
859.9 (S)	0.960

Table 1.

Measured hemispheric reflectance for P- and S-polarized light incident at an angle of450 with a polarization insensitive detector.

HEMISPHERICAL GRID