Polarimetric characterization of Spectralon

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ABSTRACT

A polarimetric characterization of the reflective standard material Spectralon is presented. Samples of Spectralon with reflectances of 2%, 50%, 75% and 99% were examined. The characterization was accomplished using the Air Force Research Laboratory's spectropolarimeter in reflection mode. Data are presented for the spectral region .65 to 1.0 micrometers. Polarizance was measured for the four Spectralon samples at eight input beam incidence angles. All observations were made from normal to the Spectralon. It was found that as the incidence beam angle increases, the polarizance increases; and as the reflectance of the sample decreases, the polarizance increases.

Keywords: Polarimetry, spectropolarimeter, Mueller matrix, Spectralon, polarizance.

1. INTRODUCTION AND BACKGROUND

Spectralon is a standard reflectance material sold by Labsphere, Inc since 1986[1]. It is composed of polytetrafluoroethylene (PTFE) powder compressed by a proprietary process into a solid[2,3]. The undoped material has a hemispherical reflectance of approximately 0.99 from 400 to 1900 nm as shown in Figure 1[4]. Spectralon also approximates a lambertian reflector, a property thought to result from a porous structure and multiple internal reflections resulting in a random distribution of reflected light. Measurement results presented by Bruegge et al[3] show a slight preference for forward scattering when illuminated by a laser off normal incidence, but no specular component was observed as shown in Figure 2. Gray and colored Spectralon is produced by introducing dopants.

The motivation for this polarimetric characterization of Spectralon originated from experiments conducted on a large reflective-optic projection system. We desired to test the hypothesis that the reflective optics would induce a polarization in the radiation from an unpolarized source. A source, consisting of a 2 in diameter sample of Spectralon illuminated by an incandescent light source through an aperture, was placed at the focus of the optical system. The projection system produces a collimated beam at its exit aperture. An imaging polarimeter was placed at this aperture and focused on the source. Results from this experiment indicated that the optical system induced a uniform polarization of approximately 3% over the face of the Spectralon. However, consideration of the method of illumination of the Spectralon sample led to a requirement for additional tests. Figure 3 shows the reflective optics test configuration. The Spectralon had to be illuminated from the side because of limited space at the sample location. Subsequent qualitative tests in the absence of intervening optics confirmed that a polarization is induced in the reflected light observed at normal incidence when the illumination is from large angles off normal.

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Data presented in the Labsphere catalog and shown in Figure 4[1] indicate that, at least under polarized illumination, the bidirectional reflectance distribution function of Spectralon is polarization dependent.

The data that is presented in this paper was taken with a spectropolarimeter developed at the Air Force Research Laboratory and described briefly below.

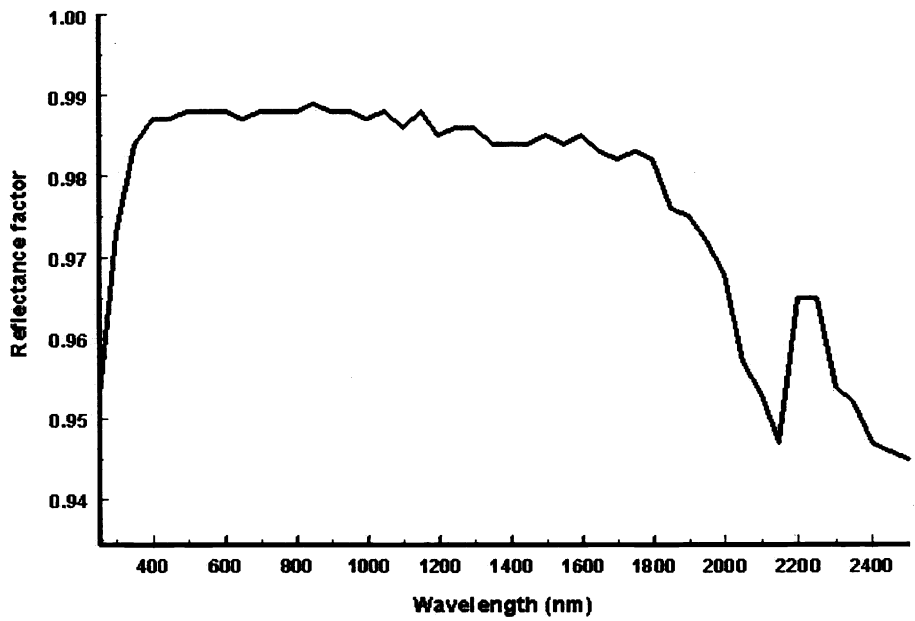

Figure 1. 8° /Hemispherical Spectral Reflectance Factor for SRS-99-020.

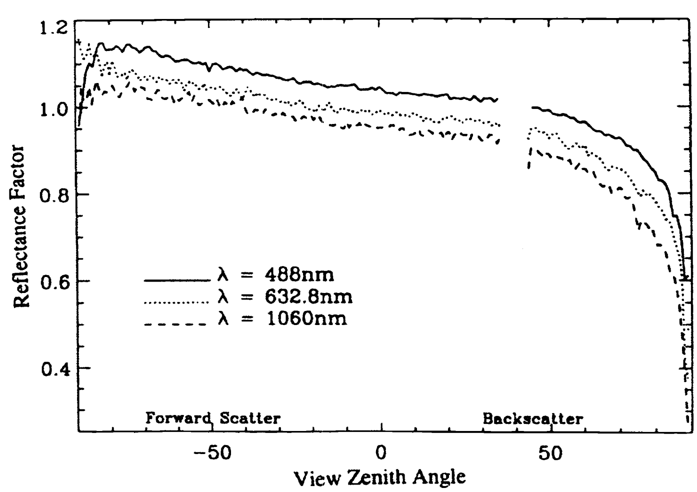

Figure 2. Reflectance factor for Spectralon illuminated with lasers at 40° (Brugge et al).

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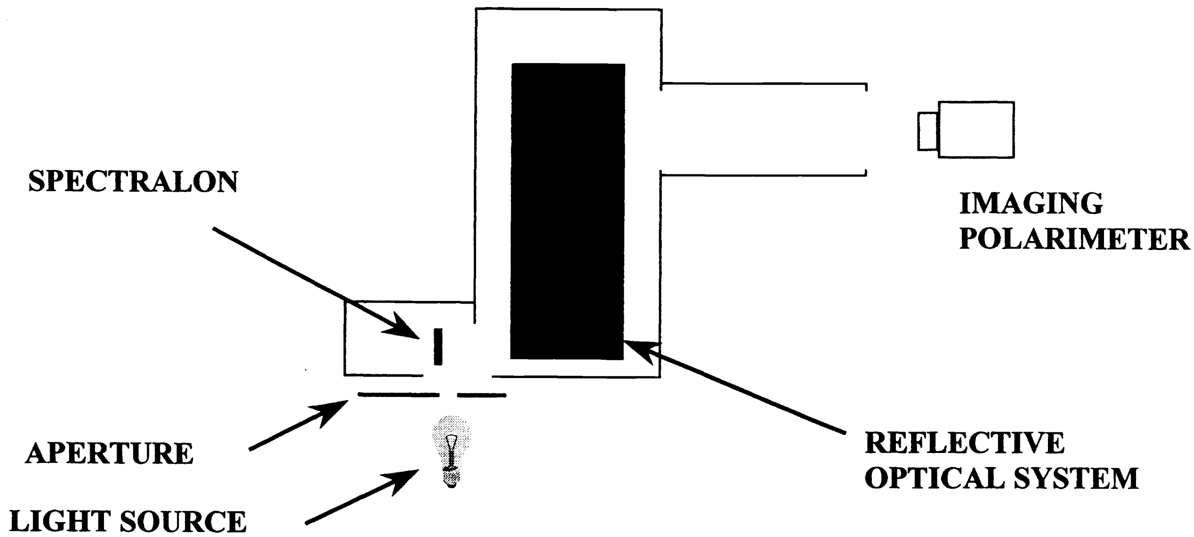

Figure 3. Reflective optical system measurement configuration.

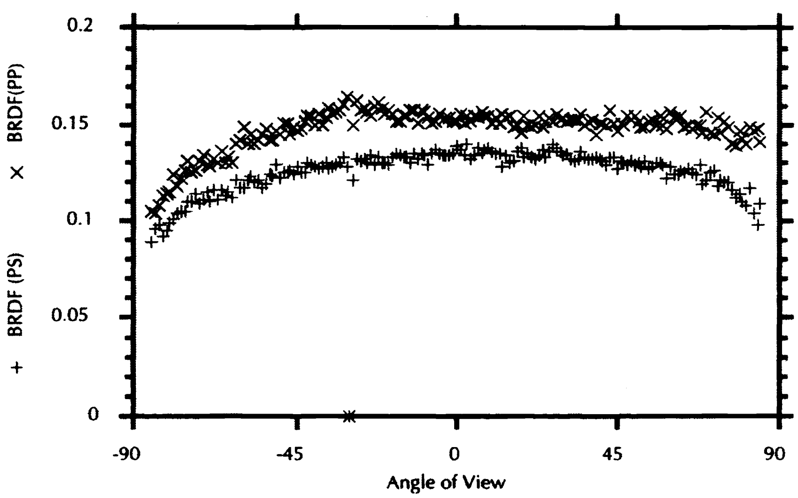

Figure 4a. In-plane BRDF for Spectralon, linearly polarized laser source (633 nm) at –30° (Labsphere).

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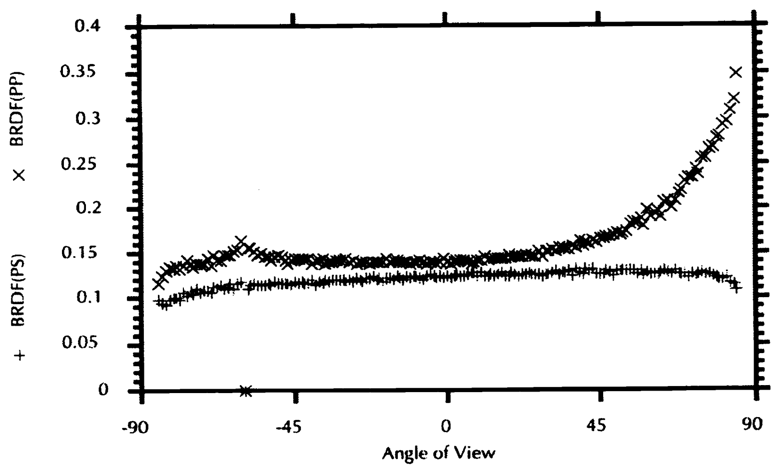

Figure 4b. In-plane BRDF for Spectralon, linearly polarized laser source (633 nm) at –60°(Labsphere).

2. FOURIER TRANSFORM SPECTROPOLARIMETRY

More than a decade ago, a spectropolarimeter based on a Nicolet Fourier transform (FT) infrared spectrometer was designed.[7,8] This instrument operates in the infrared (from 3 – 14 μm) but has high spectral resolution (better than 4 cm^{-1}). More recently, a spectropolarimeter for the visible has been developed that utilizes a broadband source and a filter wheel with suitable filters[9]. Here the spectral resolution and the number of number of spectral elements are limited by the filter bandpass and the practical size of the filter wheel.

Current FT spectrometers from a number of manufacturers operate from the ultra-violet to the infrared, covering a wavelength range from less than 0.4 to more than 25 μm. We have developed a spectropolarimeter based on one of these modern FT spectrometers. We believe that FT spectrometer-based spectropolarimeters are the most convenient and productive method of gathering large quantities of polarimetric data.

2.1 Instrumentation

The external appearance of the spectropolarimeter is shown in the photo in Figure 5. Figure 6 shows the measurement configuration. The spectrometer is operated in the normal fashion for one orientation of the polarization elements in the polarimeter. A series of spectra is taken with the polarization elements in a set of predetermined orientations. The spectra at all of the polarimeter settings (element orientations) are reduced as a single data set. Data reduction is performed on this data set one wavelength at a time resulting in Mueller matrix spectra. Further data reduction can produce diattenuation, retardance, depolarization, and other spectra.

Measurements for the present study were made from 0.4 μm to 1.0 μm. The polarization elements used in the spectropolarimetric measurements were Glan-Thompson polarizers and Karl Lambrecht achromatic retarders.

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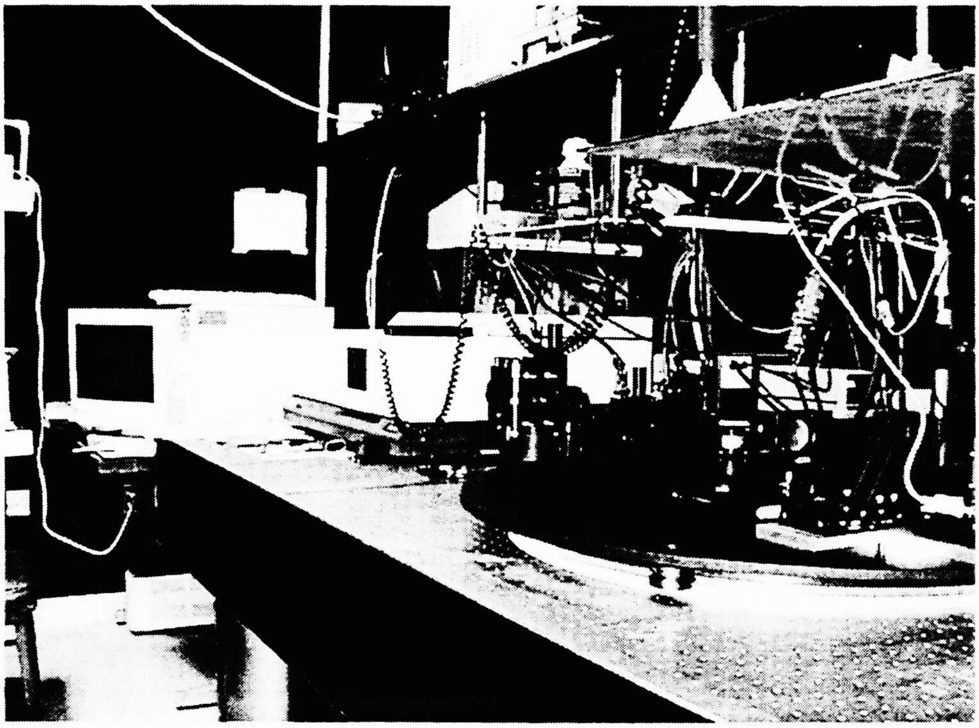

Figure 5. Photograph of FT spectropolarimeter

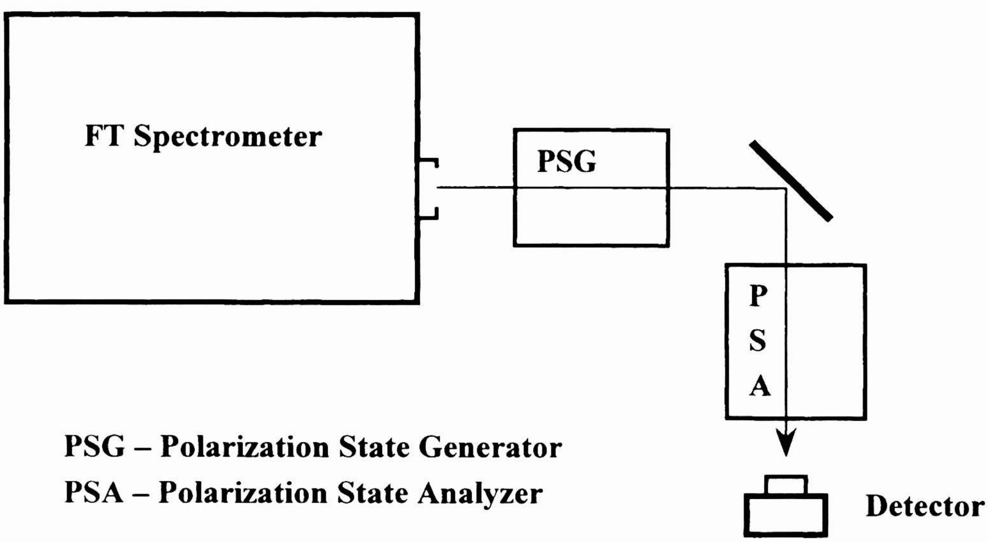

Figure 6. Diagram of FT spectropolarimeter

2.2 Data Reduction

The Mueller matrix provides the most complete polarization information about a sample and requires the most sophisticated polarimeter configuration and data reduction techniques. We have followed the dual rotating retarder method described by Azzam[11]. Figure 7 shows the configuration of a dual rotating retarder polarimeter. It consists of a sample between a polarization state generator and polarization state analyzer each comprised of a stationary linear polarizer and rotating quarter-wave linear retarder. When the retarders are rotated in a five to one ratio, all sixteen elements of the sample Mueller

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matrix are encoded onto twelve harmonics of the detected intensity signal, which can then be Fourier analyzed to recover the Mueller matrix elements. Quantities such as diattenuation, retardance, and depolarization (scattering) can be obtained from the Mueller matrix.

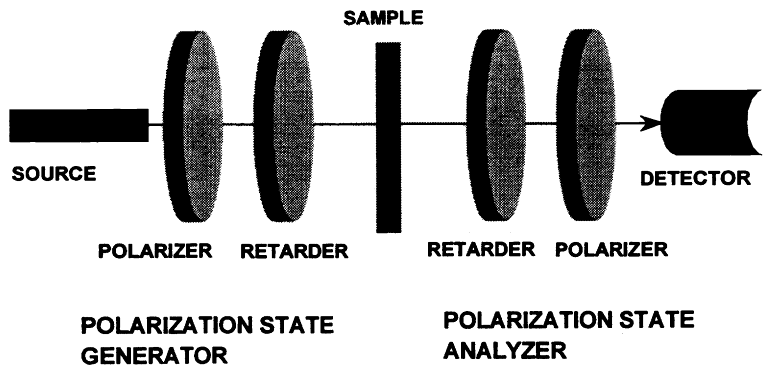

Figure 7. Dual rotating retarder configuration

The data reduction algorithm for this polarimeter as originally presented by Azzam assumes ideal polarization elements and no orientation errors. The data reduction algorithms may be generalized to compensate for systematic errors which result when orientation misalignment and non-ideal retarders are used. If the polarization elements are rotationally misaligned, or the retarders do not have exactly one-quarter wave of retardance, the changes in Fourier amplitudes and phases result in errors in the sample Mueller matrix. Even small orientation and retardance errors (<1°) can lead to large errors in the measured Mueller matrix (> 10% in some matrix elements). These errors become especially important when the retardance and alignment vary significantly from their nominal values such as in multi-wavelength or spectral instruments. We have incorporated correction terms for large orientation and retardance errors into the dual rotating retarder data reduction algorithm. The data reduction equations we have developed correct for orientation errors up to 22.5° and retardance errors up to $\lambda/8$. These equations are quite lengthy and the reader is referred to prior presentations[12].

3. EXPERIMENTAL TECHNIQUE AND RESULTS

Four samples of Spectralon having nominal reflectances of 2%, 50%, 75%, and 99% were used in the measurements. These are shown in Figure 8. The samples were placed in the spectropolarimeter and rotated to nine angles. Data were collected at these nine angles such that the detector was always aligned to the normal of the surface of the Spectralon sample. The coordinate system is shown in Figure 9, and a table of the angles used is given below. Angles measured in the clockwise direction are positive and angles measured in the counterclockwise direction are negative.

Sample	Detector
-45	135
-60	120
-75	105
-80	100
-83	97
-85	95
-87	93
-88	92
-89	91

Table 1. Sample and detector angles used in data collection.

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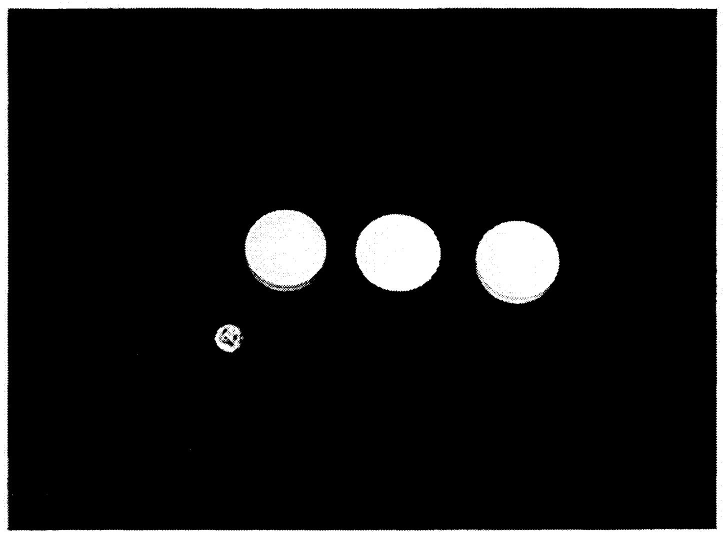

Figure 8. Spectralon samples of 2%, 50%, 75%, and 99% reflectance, left to right (a dime appears in the photo for scale).

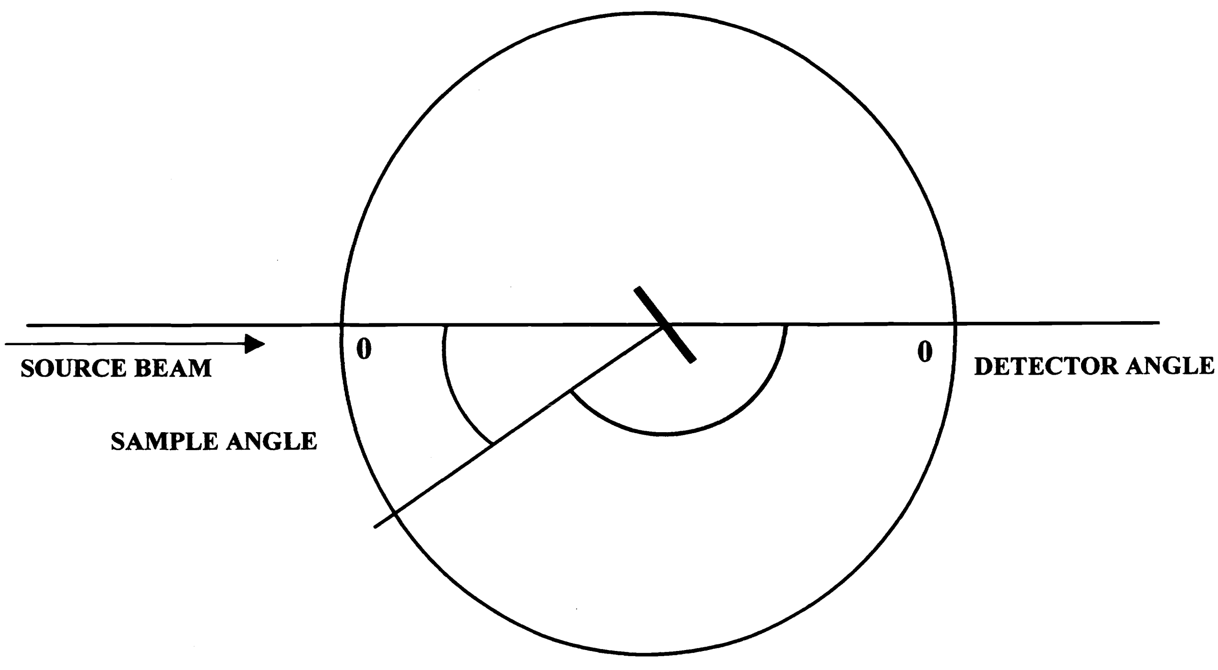

Figure 9. Spectropolarimeter coordinate system.

Data from the measurements were reduced to normalized Mueller matrices. Polarizance, the degree of polarization of the transmitted light when unpolarized light is incident[13], was computed from the Mueller matrices as

$$\mathbf{P} = \frac{\sqrt{\mathbf{m}_{10}^2 + \mathbf{m}_{20}^2 + \mathbf{m}_{30}^2}}{\mathbf{m}_{00}}.$$

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A plot of polarizance versus wavelength for the four Spectralon samples oriented at –80° is shown in Figure 10. The data that are used in all subsequent calculations and plots are for .65 to 1.0 μm. Because of the spectral content of the light source used, the signal to noise ratio of the spectrometer is poor in the .4 to .65 μm when the entire .4 to 1.0 μm spectrum is collected. Filtering of .65 to 1.0 μm light would solve this problem.

It is evident from the results plotted in Figure 10 that the polarizance of these samples is roughly constant across this spectral range and that the lower the reflectance, the higher the polarizance. The polarizance of the 2% reflectance Spectralon is noisy because of the low signal from the sample.

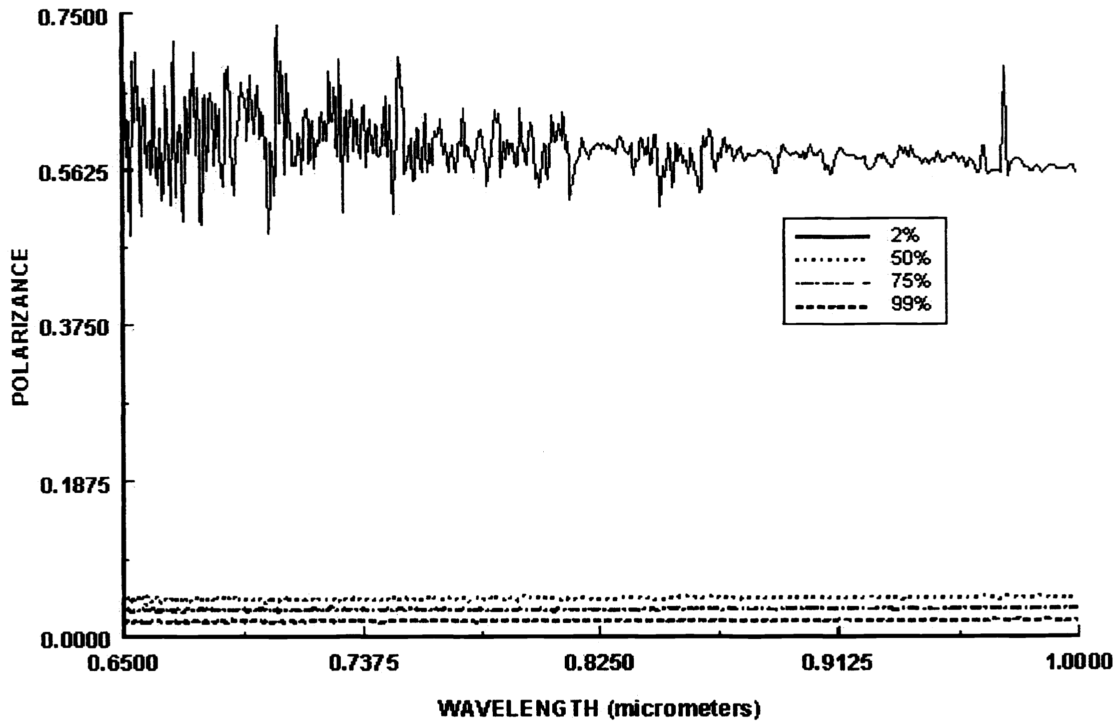

Figure 10. Spectral polarizance for four Spectralon samples, -80° source incidence angle.

The polarizance across the .65 to 1.0 μm spectral band was averaged for all subsequent analysis since it was observed to be roughly constant. Polarizance versus source beam incidence angle is plotted in Figure 11 (data from the sample angle -89° are not used, the low signal make these data very noisy). The polarizance is observed to increase as the incidence angle increases and to increase as the reflectance of the Spectralon decreases.

The polarizance versus Spectralon reflectance for each of the eight incidence angles is plotted in Figure 12. Polarizance is seen to uniformly increase with increasing incidence angle.

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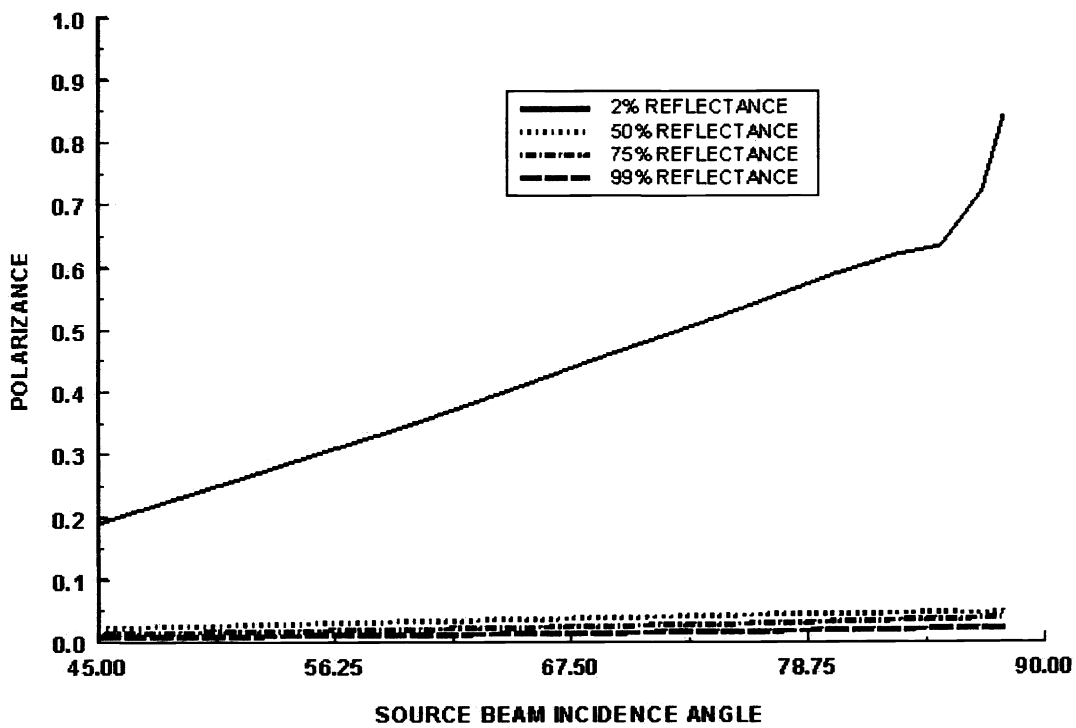

Figure 11. Averaged polarizance vs. source beam incidence angle for four values of Spectralon reflectance.

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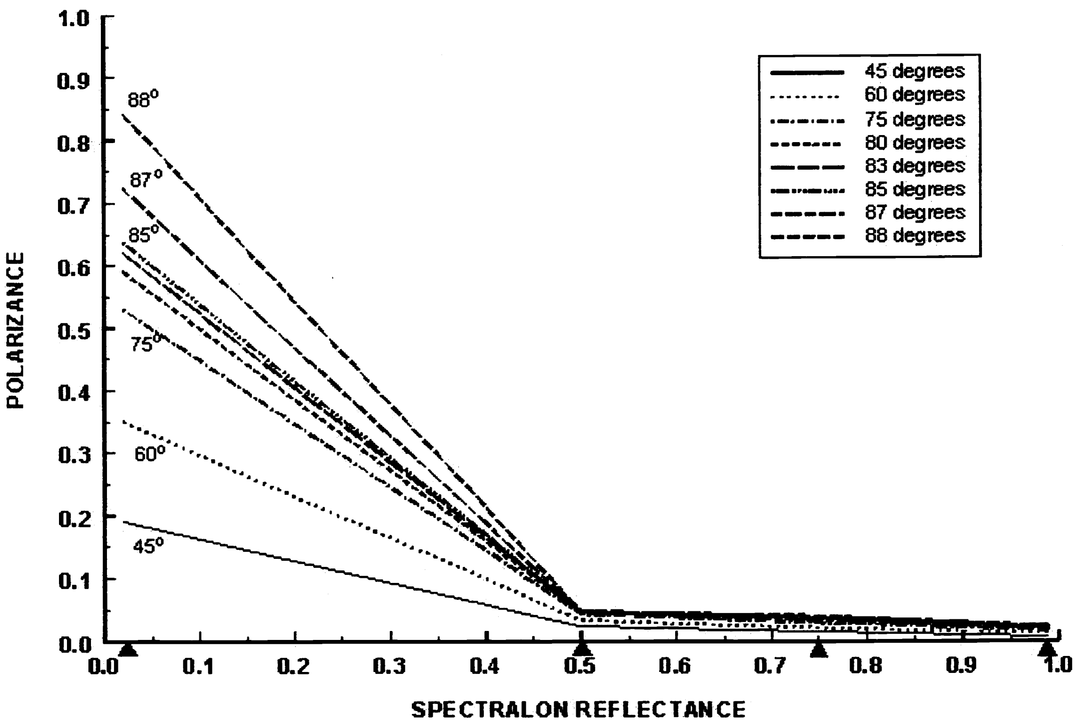

Figure 12. Averaged polarizance vs. Spectralon reflectance for eight incidence angles.

4. SUMMARY AND CONCLUSIONS

Samples of Spectralon with four nominal reflectances have been examined for polarizance over the spectral region .65 to 1.0 μm. Polarizance over this spectral region was found to be roughly constant and polarizance was averaged for all subsequent analysis. Spectralon, while a highly lambertian and predictable reflectance standard, exhibits polarizance that increases with increasing incidence angle. Polarizance also increases with decreasing reflectance.

These results tell us that the test of the reflective optical system described earlier in this paper must be done with a diffuse non-directional light source. Some of the polarization found in that test was undoubtedly due to the method of illumination of the Spectralon.

In addition to the results reported here, a large number of measurements of Spectralon were done at additional incidence angles and detector positions. These data will be used in future to perform more complete polarimetric analyses of Spectralon as a function of scatter angle.

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