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Incorporation of polarization into the DIRSIG synthetic image generation model

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ABSTRACT

The Digital Imaging and Remote Sensing Synthetic Image Generation (DIRSIG) model uses a quantitative first principles approach to generate synthetic hyperspectral imagery. This paper presents the methods used to add modeling of polarization phenomenology. The radiative transfer equations were modified to use Stokes vectors for the radiance values and Mueller matrices for the energy-matter interactions. The use of Stokes vectors enables a full polarimetric characterization of the illumination and sensor reaching radiances.

The bi-directional reflectance distribution function (BRDF) module was rewritten and modularized to accommodate a variety of polarized and unpolarized BRDF models. Two new BRDF models based on Torrance-Sparrow and Beard-Maxwell were added to provide polarized BRDF estimations. The sensor polarization characteristics are modeled using Mueller matrix transformations on a per pixel basis. All polarized radiative transfer calculations are performed spectrally to preserve the hyperspectral capabilities of DIRSIG. Integration over sensor bandpasses is handled by the sensor module.

Keywords: polarization, synthetic image generation, hyperspectral, BRDF, modeling, DIRSIG

1. INTRODUCTION

The DIRSIG model uses an integrated set of independent physics based first principles models to generate sensor reaching radiance images with a high radiometric fidelity in the 0.3–20 μm region.^{1,2} DIRSIG's modular design simplified the inclusion of polarization modeling. The DIRSIG model was upgraded to allow full polarimetric radiative transfer while minimizing the impacts to performing a traditional polarization insensitive simulation. Figure 1 shows the relationship of the DIRSIG modules which were affected by this upgrade.

The goal was to add the capability to handle polarization phenomena when and where appropriate while maintaining the speed and accuracy of the unpolarized DIRSIG model. The new polarization capabilities enable a wider range of imaging simulations with increased radiometric accuracy. The improved DIRSIG model can be used to explore polarization phenomenology. DIRSIG can generate a wide range of images to support sensor design and analysis, algorithm development and training, and imaging analyst training.²

The polarization enhancements also benefit the more traditional unpolarized simulations by providing better BRDF models. The earlier BRDF model used by DIRSIG was a simple diffuse model with a parameterized specular lobe.³ In addition, the polarized radiative transfer model also yields more accurate unpolarized sensor reaching radiance estimations.

Polarized synthetic image generation (SIG) is still in its infancy and has many opportunities for improvement. Therefore, it was highly desired to incorporate the polarization modeling in a way that enables side-by-side polarized and unpolarized calculations. The resulting modeling environment is modularized to facilitate future improvements in polarization modeling.

This paper briefly describes the modifications made to each of the modules shown in figure 1. The major focus of this paper is the improvements made to the BRDF modeling. The modified Torrance and Sparrow BRDF model is extensively characterized to demonstrate the significant impacts of polarimetric BRDFs. Finally, a simple image is presented that demonstrates the successful simulation of an ideal polarimetric imaging system.

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Figure 1. DIRSIG flow chart.

2. IMPLEMENTATION

This section describes how the polarization modeling was implemented in the new version of DIRSIG. The DIRSIG computer code underwent a total rewrite to accommodate polarization modeling requirements. The most significant factor was the requirement to perform polarized, full spectral radiometric calculations. This required the implementation of Stokes vectors for the radiance quantities and Mueller matrices for the energy-matter interactions. Modifications were also made to the BRDF and sensor models to support the polarimetric calculations. Additional considerations included maintaining the hyperspectral nature of the DIRSIG model and the modular design.

2.1. Polarization Calculations

The polarization state of radiance values can be fully characterized using the Stokes vector formalization. A Stokes vector is composed of the four Stokes parameters: S_0 , S_1 , S_2 , and S_3 (older literature commonly refers to the Stokes parameters as I , Q , U , and V , respectively). The Stokes vector is written as

$$\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad (1)$$

where S_0 is the total radiance and the other three parameters indicate relative values of linear and circular polarization states. Collet⁴ defines the Stokes parameters as

$$S_0 = \langle \mathcal{E}_x^2 \rangle + \langle \mathcal{E}_y^2 \rangle \quad (2)$$

$$S_1 = \langle \mathcal{E}_x^2 \rangle - \langle \mathcal{E}_y^2 \rangle \quad (3)$$

$$S_2 = 2 \langle \mathcal{E}_x \mathcal{E}_y \cos \delta \rangle \quad (4)$$

$$S_3 = 2 \langle \mathcal{E}_x \mathcal{E}_y \sin \delta \rangle \quad (5)$$

where $\vec{\mathcal{E}}$ is the electric field and the subscripts indicate the component of the electric field in the plane containing the propagation axis (z) and the subscripted axis. One method of measuring the Stokes parameters uses four detectors, a set of linear polarizers, and a right circular polarizer. The first detector measures the total radiance, the other three detectors measure the radiance transmitted by each of the three polarizers. One of the linear polarizers is aligned horizontally and the other is aligned at an angle of 45° from the horizontal axis. This setup

results in the following equations for calculating the Stokes parameters:

$$S_0 = L_0 \quad (6)$$

$$S_1 = 2L_1 - L_0 \quad (7)$$

$$S_2 = 2L_2 - L_0 \quad (8)$$

$$S_3 = 2L_3 - L_0 \quad (9)$$

where L_n corresponds to the radiance measured by the corresponding detector. Stokes vectors can have units of irradiance or radiance depending on the radiometric quantity being characterized. A single detector system can be used to measure the Stokes parameters if the filters are placed on a filter wheel and the radiance field is stable over the time required to measure all four radiances.

The unpolarized version of DIRSIG simply dealt with the value associated with the S_0 Stokes parameter. The polarized model needs to store three additional quantities for each radiance value. This requires a four-fold increase in memory storage. Since the S_0 parameter directly relates to the unpolarized radiance value used previously, it is relatively simple to transition between polarized and unpolarized computations on-the-fly. This simplifies the integration of polarized and unpolarized modules within the overall DIRSIG model.

The introduction of Stokes vectors to characterize the radiance values requires the use of Mueller matrices and Mueller calculus to fully characterize the energy-matter interactions.⁴ In the most general case, partially polarized irradiance is incident upon a surface which reflects partially polarized radiance with different polarization characteristics. The coupling of these two Stokes vectors requires a 4×4 Mueller matrix. Once again, the unpolarized version of DIRSIG used a single value to characterize these interactions. The need for Mueller matrices increases memory usage by a factor of sixteen. Unlike the Stokes vector case, there is no direct correlation between the single value used previously and one of the Mueller matrix entries; however, m_{00} is the closest. The general matrix equation for relating two Stokes vectors is given by the matrix equation

$$\mathbf{S}_{\text{out}} = \mathbf{M} \cdot \mathbf{S}_{\text{in}}. \quad (10)$$

The Mueller matrix M is given by

$$M = \begin{pmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{pmatrix}. \quad (11)$$

Brosseau⁵ and Collett⁴ provide detailed information on the relationships among the sixteen Mueller matrix elements. Figure 2 shows how the Stokes vectors and the BRDF Mueller matrix interact for a simple reflection scenario. All of the Stokes vector and Mueller matrix quantities vary spectrally.

2.2. Polarized BRDF

The BRDF is defined as the ratio of the reflected radiance to the incident irradiance for a given geometry.⁶ In the most general case, the BRDF is a function of four angles: the incident azimuth and zenith and the reflected azimuth and zenith. In the case of isotropic reflectors, the circular symmetry introduces redundancy which can be eliminated by expressing the BRDF as a function of the two zenith angles and the difference of the two azimuth angles. Currently, DIRSIG models all materials isotropically. Earlier versions of DIRSIG used a simplified Lambertian BRDF model with a parameterized specular lobe. This model did not provide enough flexibility for polarimetric modeling. Therefore, new BRDF models were considered. The result is a modularized BRDF module which can be expanded to include a wide range of appropriate BRDF models.

Currently two polarized models have been implemented, a Torrance and Sparrow⁷ based model and a Beard-Maxwell⁸ based model. Both models are microfacet based models which assume the BRDF of a single facet can be modeled by multiple specular returns from a random orientation of surface microfacets.⁹

Figure 2. Mueller matrix illustration and BRDF geometries. The Stokes vectors (E_i and L_r) and the BRDF Mueller matrix (M) are all functions of the wavelength (λ). The subscripts i and r relate to the macrofacet and the subscript N relates to the specular microfacet.

2.2.1. Torrance and Sparrow BRDF model

Torrance and Sparrow developed a simple unpolarized BRDF model for predicting the off-specular reflections from roughened surfaces.⁷ The model used a microfacet surface model and was based on three physical parameters, the complex index of refraction (n and k) and the surface roughness, σ . The model assumes a Gaussian slope distribution for the microfacets and the surface roughness parameter is the standard deviation.

Torrance and Sparrow also introduced the concept of a shadowing and obscuration function (SO). The SO function calculates what percentage of the specular microfacet surfaces are illuminated by the incident radiation and therefore contribute to the reflected radiance field. The complex index of refraction is used to calculate the Fresnel reflection from the specular microfacets. Priest and Germer polarized the Torrance and Sparrow model by combining it with the Mueller matrix for a microfacet surface.⁹ The equation for the polarimetric BRDF is given in Priest and Germer⁹ as

$$f_{j,k}(\theta_i, \theta_r, \phi_r - \phi_i) = \frac{1}{2\pi} \frac{1}{4\sigma^2} \frac{1}{\cos^4(\theta)} \frac{\exp(-\frac{\tan^2(\theta)}{2\sigma^2})}{\cos(\theta_r) \cos(\theta_i)} M_{j,k}(\theta_i, \theta_r, \phi_r - \phi_i) \quad (12)$$

where j and k are the indices of the Mueller matrix, θ (with no subscript) is the angle of incidence and reflection for the specular microfacets generating the return for the given geometry, θ_i and θ_r are the zenith angles, ϕ_i and ϕ_r are the azimuth angles, σ is the surface roughness parameter, and M is the microfacet Mueller matrix. The subscripts i and r refer to the incident and reflected directions respectively.

The microfacet model is a single reflection model which does not predict any depolarizing contributions from multiple bounces and subsurface interactions. Welles et. al. proposed estimating a diffuse, depolarizing term by integrating the BRDF over the entire hemisphere for a perfectly reflecting microfacet surface with a given surface roughness. The difference between the integrated value and 1.0 can be attributed to diffuse scattering resulting from multiple bounces and subsurface interactions.¹⁰ This depolarizing term is a function of only the surface roughness and not the material's complex index of refraction. This depolarizing term is included as an optional term in the DIRSIG implementation of the Torrance and Sparrow BRDF model.

Another common modification to the Torrance and Sparrow model is a variation in the microfacet normal distribution function. The original model used a Gaussian distribution as shown in equation (12). The Cauchy distribution is another popular choice for the microfacet normals. Currently the DIRSIG implementation only

uses a Gaussian distribution, but providing the user with the option of using a Cauchy distribution is being considered.

The simplicity and first principles base approach of the Torrance and Sparrow model make it an ideal candidate for inclusion in the DIRSIG model. However, the simple assumptions of the BRDF model result in some significant limitations. The model only accounts for first surface scattering and is not well suited for materials with significant volume scattering contributions. The only depolarizing contribution comes from the Wellems estimation.

Additionally, the model assumes knowledge of the material's complex index of refraction. In practice, the complex index of refraction is a very difficult parameter to measure. Often the three model parameters are determined empirically for a given material sample based on a series of BRDF measurements. A major disadvantage of this approach is the abandonment of the first principles nature of the model. The resulting parameter values simply become empirical quantities which are not necessarily constrained by their physical representations.

Finally, the Torrance and Sparrow model breaks down mathematically for grazing angles. This results from the cosines in the denominator of equation (12).

2.2.2. Beard-Maxwell BRDF model

The Beard-Maxwell⁸ BRDF model is also a microfacet based model with many similarities to the Torrance and Sparrow model. Like the Torrance and Sparrow model, the Beard-Maxwell model was originally developed to predict unpolarized BRDFs. However, the basic principles of the model allow for a polarimetric extension analogous to the one applied to the Torrance and Sparrow model.

The major advantages of the Beard-Maxwell model is the inclusion of depolarizing scattering terms and a potentially larger database of model parameter values. The Nonconventional Exploitation Factors (NEF) database, maintained by the National Imaging and Mapping Agency (NIMA), contains empirically derived parameters for a variety of materials. Unfortunately, the parameter values were derived for unpolarized applications and therefore do not extrapolate well for polarimetric modeling. A more physically constrained parameter estimation method should result in parameters better suited to a polarimetric extension of the Beard-Maxwell model.

2.3. Solar and Atmospheric Contributions

DIRSIG uses MODTRAN¹¹ to calculate solar and skylight radiance values as well as atmospheric transmissions. The current version of MODTRAN does not support polarimetric calculations. However, DIRSIG's modular design will easily incorporate an upgraded polarimetric version of MODTRAN as soon as it becomes available.

A polarized version of MODTRAN is currently being developed by the Air Force Research Lab (AFRL). We are working closely with AFRL to ensure the polarized version of MODTRAN will integrate with DIRSIG as soon as it is available. Until a polarized version of MODTRAN is available, simulations are limited to assuming completely unpolarized solar and sky illumination. An alternative would be to substitute measured solar and sky irradiance data for the MODTRAN inputs. This option was not explored due to a lack of measured data.

The DIRSIG simulations presented in this paper used simple point source illuminations and do not use any version of MODTRAN to estimate sky radiances. These simple illumination scenarios simplified the validation and testing of the new polarization capabilities. More complicated illumination scenarios simply result in the linear combination of the contributions from each individual illumination source.

2.4. Polarized Sensor Model

The DIRSIG sensor models can be polarized on a per pixel basis using a Mueller matrix transformation function. This approach allows one to fully characterize the polarimetric response of a real or simulated sensor. By characterizing the sensor on a pixel-by-pixel basis, it is possible to introduce polarization sensitivities as a function of the focal plane location. DIRSIG is not intended to model each internal component of a sensor; therefore, it does not perform a rigorous physics based simulation of the optical components. However, it does

model many of the physical aspects like platform motion, off-axis imaging, and image formation techniques (i.e. framing array versus scanning systems) which contribute to the overall system MTF and allows the user to describe the net effects of detailed sensor models for each detector element.

A simple example of how the polarized sensor model can be used involves simulating a four camera polarimetric imaging system. Each camera is a simple 2-D framing array system with a polarizing filter in front of the optics. The filters are chosen such that the four resulting images can be processed to produce S_0 through S_3 Stokes parameter images. This type of system can be easily simulated in DIRSIG by applying the appropriate Mueller matrix for each filter to the radiance field reaching each of the imaging systems. If a per pixel calibration is available for each of the four cameras, a different Mueller matrix can be specified for each pixel in the system. This type of approach can be expanded to any type of imaging system that DIRSIG supports.

3. RESULTS

The behavior and characteristics of the polarization related modules in DIRSIG are presented in this section. First, the characteristics of each module are presented independently. Finally, the results of combining all of the polarization enhancements are presented in a series of synthetically generated images demonstrating polarization phenomena. The scene used for these simulations was kept very simple to allow us to study and verify the proper implementation of the polarization phenomena. However, these polarization modeling capabilities are also available for more complex geometric scenes.

3.1. Torrance-Sparrow BRDF Visualization

The complex nature of a fully polarimetric BRDF is difficult to capture in a single figure. The following sections show the effects of variations in the BRDF model parameters. A combination of zenith and azimuthal plots are used to quantitatively characterize the BRDF. The variation in specular lobe width and location is characterized. A full characterization of the polarized BRDF model requires analyzing all sixteen Mueller matrix elements. To simplify the characterization, this paper considers those elements most significant when dealing with unpolarized illumination. In the following sections, the notation f_{ij} refers to the $[i, j]$ element of the BRDF Mueller matrix.

3.1.1. Surface roughness effects

The surface roughness parameter, σ , has a large impact on the shape and characteristic of the BRDF. Plots of the f_{00} element of the BRDF Mueller matrix correlate closely to unpolarized BRDF values. Plots of f_{00} in the plane of incidence (i.e. $\phi_i - \phi_r = \pm 180$ deg) show the specular lobe characteristics of the BRDF model (see figure 3).

The BRDF plots in figure 3 are for roughened aluminum. The simulations used values of $n = 1.304$ and $k = 7.479$ which correspond to a wavelength of 620 nm.¹² The incident zenith angle is 45° and a Gaussian microfacet distribution was used. The plots show how the surface roughness parameter, σ , affects the specular lobe shape and location. As the roughness increases, the BRDF becomes less specular, the lobe width increases, and the peak of the lobe shifts to larger zenith angles. The shift in forward scattering is predicted by the model and was observed in measured data by Torrance and Sparrow.⁷ The rougher surfaces (figure 3(b)) also show the effects of the shadowing function which is prominent above 75° .

The azimuthal characteristics of the polarization sensitive elements f_{10} and f_{20} are shown in figure 4. For the case of unpolarized illumination, these two Mueller matrix elements determine the amount and orientation of the linear polarization in the reflected radiance. Once again, the shape of the curves decrease in height and increase in width as the roughness increases. Also note that f_{10} peaks and f_{20} changes sign as the reflected angle passes through the plane-of-incidence.

The plots in Figure 5 show how the location and width of the specular lobe varies as a function of the incident zenith angle and the surface roughness. Once again, values of $n = 1.304$ and $k = 7.479$ were used. The forward shift of the specular lobe location is linear for zenith angles less than 50° . The specular lobe width was defined as the full width at half the maximum value (FWHM). The lobe width is dependent mostly on the surface roughness. As the surface roughness increases, the lobe width tends to increase slightly with increasing zenith angles. The large decrease in lobe width for the roughest materials is actually caused by a "clipping" or

(a) Smooth surfaces

(b) Rough surfaces

Figure 3. In-plane Torrance-Sparrow BRDF (f_{00} Mueller matrix element) plotted as a function of the reflected zenith angle, for an incident zenith angle of 45° .

(a) Smooth surface, $\sigma = 0.10$ rad

(b) Rough surface, $\sigma = 0.20$ rad

Figure 4. Out-of-plane Torrance-Sparrow BRDF (f_{10} and f_{20} Mueller matrix elements) plotted as a function of the reflected azimuth angle for an incident zenith angle of 45° .

“masking” of the specular lobe at the horizon. Since the specular lobe can’t extend past a zenith of 90° , the lobe width is truncated at the horizon resulting in artificially small widths as the lobe’s location approaches the horizon. This phenomenon is shown in figure 3(b).

3.1.2. Index of refraction effects

The previous section presented the effects of varying the material’s surface roughness parameter. Now we present the impacts of varying the values of n and k . The values of n and k are instrumental in identifying the material. For example non-metallic materials tend to have small k values or k values of zero. Whereas metals will have significantly larger k values. One of the most common optical characteristics associated with the index

Figure 5. Torrance-Sparrow BRDF specular lobe characteristics for Aluminum at 620 nm.

Figure 6. Torrance-Sparrow BRDF as a function of the real component of the index of refraction.

of refraction is the Brewster angle (or pseudo-Brewster angle for metals). The values of n and k also have a large impact on the BRDF characteristics.

The plots in figure 6 show the effects of varying the real part of the index of refraction, n while holding k constant at 0. The zenith angle of incident was 10° and the reflected angle was kept in the plane of incidence. The two graphs show how the surface roughness interacts to create a specular versus diffuse reflector. Both graphs exhibit secondary peaks at extremely high grazing angles. In this region, all four plots overlaid each other. This phenomenon is caused by the addition of the estimated diffuse term. Since the diffuse term is only a function of the surface roughness, it will be the same for all materials. As the index of refraction increases, so does the magnitude and width of the specular lobe. However, unlike the surface roughness parameter, there is no shift in the location of the peak. The two graphs also show how a small variation in the surface roughness parameter can lead to a quick transition from a highly specular material to a predominantly diffuse one. The transition is more pronounced for smaller values of n .

The plots in figure 7 show the effects of varying the imaginary part of the index of refraction, k , while

Figure 7. Torrance-Sparrow BRDF as a function of the imaginary component of the index of refraction.

holding n constant at 1.7. The zenith angle of incident was 10° and the reflected angle was kept in the plane of incidence. The bottom curve ($k = 0$) in figure 7(a) is the same as the $n = 1.7$ curve in figure 6(b). This indicates that increasing the value of k increases both the specular lobe peak and lobe width without changing the lobe location.

Another significant effect of changing the value of k is the introduction of circular polarization which results in elliptical polarization when combined with the linear polarizations. The curves in figure 7(b) show that f_{23} becomes non-zero when k is non-zero. Since $f_{32} = -f_{23}$, the same applies for f_{32} . These two terms are responsible for converting $\pm 45^\circ$ linear polarization into circular polarization. Also note that the peak in f_{23} is not in the specular direction. Finally, the effects of the shadowing function start to appear around a zenith angle of 70°.

3.2. Comparison with Measured Data

Roughened metallic surfaces are excellent candidates for testing the modified Torrance and Sparrow BRDF model. Reflections from metal surfaces are dominated by first surface reflections and there is essentially no subsurface or volume scattering involved.

BRDF-like measurements were made of two copper plates (figure 8) using an ASD field spectrometer with a three degree field of view optic. The data measured are not truly BRDFs as defined by Nicodemus et. al.⁶ because we used an extended light source to provide an uniform illumination over the entire sample. The BRDF was estimated by calculating the ratio of the radiance reflected by the metal sample to the radiance reflected by a diffuse spectralon reference. Both copper plates were roughened by sandblasting them, one with 60 grit and the other with 150 grit sand.

The n and k values for the Torrance and Sparrow BRDF were obtained from the CRC tables.¹² Next, the Torrance and Sparrow BRDF was calculated for multiple surface roughnesses and the best curve was chosen for each data set. The process was repeated at two wavelengths to investigate if the surface roughness parameter is truly independent of wavelength as assumed by the model. Figure 8 shows that the Torrance and Sparrow predictions follow the general trend of the measured data. The most significant deviations occur outside the main lobe region. This suggests the distribution of microfacet normals may differ from the assumed Gaussian distribution. Better characterization of the microfacet distribution should improve the accuracy of the model.

Another factor contributing to the differences is the measurement of the incident and reflected zenith angles. The light source and ASD optic were mounted on two separate tripods. While the light source remained fixed

Figure 8. Comparison of measured BRDF (points) and Torrance-Sparrow predicted BRDF (lines).

throughout all of the measurements, the detector's tripod was moved along a line in the plane of incidence. The angles were calculated using trigonometric relationships between the horizontal and vertical distances from the center of the sample.

3.3. DIRSIG Polarimetric Images

Figure 9 shows the results of combining all of the DIRSIG polarization upgrades. The scene is a simple geometry consisting of a Lambertian ground plane with four truncated pyramids. The material properties of the four pyramids are identical except for the surface roughness assigned to each. The index of refraction was chosen to simulate copper at 620 nm. The scene was imaged using a simulated framing array optical system from directly over head. The single point source illumination came from the upper right-hand corner of the scene and was completely unpolarized.

The S_0 image, figure 9(a), corresponds to the image that would result from a polarimetric insensitive imaging system. The histograms of all four images were stretched to highlight the variations. The apparent brightness of each pyramid increase clockwise starting with the lower left corner being the darkest. This corresponds to the increasing surface roughness of each pyramid. The four pyramids have surface roughnesses of 0.15 rad, 0.20 rad, 0.25 rad, and 0.30 rad respectively. Since the rougher materials have a wider specular lobe, there is a greater chance for off-specular incident light to be reflected.

A more complex pattern is present in the degree of polarization (DoP) image. In this case, the DoP of the tops of the pyramids, decrease slightly with increasing surface roughness while the DoP of the sloping sides increase. The complexities of the DoP variations are due to the scene and illumination geometries and the differences in BRDF structure as a result of surface roughnesses. While the absolute reflected radiance has an influence on the DoP, in general, the DoP image will contain different information than the standard S_0 image.

4. CONCLUSIONS

We have successfully demonstrated the ability to perform polarimetric radiometry simulations resulting in a synthetically generated sensor reaching radiance image. The radiative transfer calculations can be performed using either polarized or unpolarized quantities in the same simulation based on the availability of polarimetric input parameters. The resulting simulation includes as much polarization information as possible about the simulated scene.

(a) S_0 image

(b) S_1 image

(c) S_2 image

(d) DOP image

Figure 9. Simple DIRSIG polarimetric simulation.

A lack of polarimetric BRDF databases poses the single largest problem for conducting fully polarimetric radiometry simulations. Physically based BRDF models exist that do an acceptable job of predicting the polarimetric BRDF. However, resource limitations have prevented generating databases of physically based model parameters. Empirically derived parameters tend to work well for specifically measured materials. However, the empirical method severely limits the ability to extrapolate the results to unknown conditions. As better models and material databases become available, the simulated results will also improve.

DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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