Evaluation of the Suitability of Polarimetric Scattering and Emissivity Models with Scene Generation Software

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ABSTRACT

Software based polarimetric image generation models and hardware based infrared scene projectors commonly utilize analytical forms of polarized bi-directional reflectance distribution function and emission models. Many of these models are based in first principles physical concepts, but in practice are configured as least error fits to measured signatures. The resulting analytical model may well describe the lab measured data points, but provide erroneous results when integrated into a wide ranging radiometric simulation environment. In this work we present a methodology for characterizing the suitability of incorporating limited range lab measured data, usually through fitting to an analytical model, into a wider range modeling environment. We have found lab measured reflectance data can be fit to analytical models with parameters straying significantly from the first principles physical description of the surface. This effect may be due to over parameterization or an under sampled measurement space, resulting in radiometric anomalies when integrated into a larger scale, multi-surface, multi-material, modeling environment. Our methodology consists of a series of sanity tests that each scattering and emission model configuration must pass before confidence is had in the polarimetric optical property description.

Keywords: Modeling, simulation, optical properties, polarization.

1. INTRODUCTION

The needs of the tactical remote sensing community are quite dynamic, often requiring a variety of imaging modalities to adequately characterize areas of interest. One such modality that often aids in improving contrast between man-made targets and natural background clutter is polarimetric imaging [1]. In many cases, polarimetric imaging sensors and payloads can benefit greatly from polarization capable synthetic image generation software [2] as well as polarization capable scene projectors [3]. However, at the core of both image simulation models and scene projection hardware is the requirement of a solid understanding of surface level polarimetric reflectance and emissivity properties.

The Digital Image and Remote Sensing Image Generation (DIRSIG) software model [2] has been capable of fully spectral and polarimetric radiative transfer and image generation for over 10 years. Two example DIRSIG polarimetric image outputs are shown below in Figure 1. However, the weak link in the model has historically been adequate polarimetric optical property descriptions for a wide range of materials. Existing material reflectance and emissivity databases are commonly leveraged for modeling of large scale scenes, while smaller scale scenes might have objects attributed with scene specific and locally (at the Rochester institute of Technology) measured optical properties. In either case, the challenge tends to be providing an empirical description of lab measured data to the models. Working inside the geometric and spectral bounds of lab measurements can provide the best results, but is not a guarantee of radiometrically accurate simulated results due to a variety of issues to be discussed in this paper.

Figure 1. Example polarimetric image simulations of a ground (top) and space (bottom) based target using the DIRSIG model.

2. GENERALIZED, POLARIMETRIC SCATTERING AND EMISSION MODEL

The common backbone of both polarized reflectance and emissivity models is the polarimetric bi-directional distribution function (pBRDF). Generally, there are two main classes of material scattering models utilized in the polarimetric remote sensing community, namely man-made target [1, 4, 5] and natural clutter models [1, 2, 3]. The man-made target BRDF model (Eq. 1) typically takes the form of a micro-facet reflectance function (Eq. 2) coupled with a variety of volume or bulk material scattering terms (Eq. 3). A schematic showing the scattering geometry related to both terms is shown below in Figure 2.

$$f(\lambda, \theta_i, \phi_i, \theta_r, \phi_r, n, k, \dots) = f_1(\lambda, \theta_i, \phi_i, \theta_r, \phi_r, n, k, \dots) + f_{bulk}(\lambda, \theta_i, \theta_r, n, k) \quad (1)$$

The first surface scatter term, sometimes referred to as the specular term, is a function of an arbitrary gain value ρ_s , a surface facet slope probability distribution (which may be based on measured values or simply a closed form distribution model such as a Gaussian or Cauchy) p , a 4x4 element Fresnel reflectance Mueller matrix $R_{fresnel}$ taking wavelength dependent complex index of refraction values and the scatter half angle β as inputs, a potentially complex or absent shadowing and obscuration function $SO(\dots)$, and the incident and reflected zenith angles θ_i and θ_r respectively.

$$f_1(\lambda, \theta_i, \phi_i, \theta_r, \phi_r) = \frac{\rho_s \cdot p(\sigma(\lambda), \theta_{mf}) \cdot R_{fresnel}(\beta, n(\lambda), k(\lambda))}{4 \cdot \cos \theta_i \cdot \cos \theta_r} \cdot SO(\dots) \quad (2)$$

The “bulk” material scattering term of the generalized polarimetric BRDF contains three sub terms, one that is perfectly Lambertian ρ_L , one that is a modified Lambertian form containing the value ρ_v , and one that is some portion ρ_B of bulk, multiply scattered light that induces polarization via the 4x4 element Mueller transmission matrix T_{fresnel} .

$$f_{\text{bulk}}(\lambda, \theta_i, \theta_r, n, k) = \rho_B \cdot T_{\text{fresnel}}(\theta_r, n(\lambda), k(\lambda)) + \rho_L + \frac{\rho_v}{\cos \theta_i + \cos \theta_r} \quad (3)$$

This generic form the polarimetric BRDF can be configured to represent the modified Beard-Maxwell BRDF model utilized by the Nonconventional Exploitation Factors (NEF) database, the Priest-Germer microfacet model, the Torrance and Sparrow BRDF, and a variety of others with subtle differences. The Rochester Institute of Technology has implemented this generic BRDF into its DIRSIG radiative transfer model in order to support material properties from a variety of origins.

A quantity that is often derived from the full form of the BRDF is the Directional Hemispherical Reflectance (DHR) function (sometimes referred to as the diffuse hemispherical reflectance) which has the form

$$DHR(\theta) = \int_0^{2\pi} \int_0^{\pi/2} f(\theta_i, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \quad (4)$$

Figure 2. Schematic of scattering geometry for 1st surface and bulk scattered light utilized by a generalized polarimetric scattering model.

The hemispherically integrated BRDF for a given angle of incidence, or $DHR(\theta_i)$, is quite useful and employed commonly for modeling directional emissivity signatures in a polarimetric radiative transfer framework [9,10]. More specifically, the equation for the Stoke’s emissivity vector (Eq. 5) for a given material is expressed as

$$\varepsilon(\theta) = \begin{bmatrix} 1 - \int_0^{2\pi} \int_0^{\pi/2} f_{0,0}(\theta, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \\ - \int_0^{2\pi} \int_0^{\pi/2} f_{1,0}(\theta, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \\ - \int_0^{2\pi} \int_0^{\pi/2} f_{2,0}(\theta, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \\ - \int_0^{2\pi} \int_0^{\pi/2} f_{3,0}(\theta, \theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \end{bmatrix} \quad (5)$$

where the subscript on the BRDF function f in the integrands corresponds to the row and column of the full BRDF Mueller matrix.

3. SPECTRAL INTERPOLATION OF POLARIMETRIC BRDF MODELS

It is often the case, such as with the NEF materials database, that the high angular fidelity BRDF measurements are conducted at a small number of wavelengths (i.e. laser wavelengths around 328 nm, 632nm, 1.06 microns, 3.39 microns and 10.6 microns). These lab based measurements are typically augmented by high spectral resolution directional hemispherical reflectance measurements at one specific angle of incidence. The result is two somewhat disparate pieces of information: (1) high angular fidelity, low spectral fidelity goniometer measurements fit to an empirical model and (2) low angular fidelity, high spectral fidelity integrating sphere measurements.

The job of spectrally interpolating a BRDF model leverages both pieces of information to hopefully bridge the gaps for accurate spectral, polarimetric image simulations and scene projections. We have encountered three different approaches to spectral interpolation which are summarized in Table 1.

Table 1. Summary of Existing pBRDF Spectral Interpolation Approaches

Type	Interpolation Description	Suitability	Requirement(s)
I	Linear interpolation of modeled BRDF between reference wavelengths	First surface dominated materials that have well known complex index of refraction values that adequately resolve all spectral features over desired wavelength range <i>Examples: Solid metals, optically opaque and homogeneous liquids</i>	Parameterized BRDF at a small number of sparsely spaced wavelengths
II	Linear interpolation of 1 st surface scatter term of BRDF between reference wavelengths. Apply wavelength dependent gain to “bulk” scatter BRDF term such that the resulting hemispherical integration of full BRDF matches the lab measured DHR spectrum	Materials possessing a combination of 1 st surface and bulk scattering behaviors for which the magnitude of the specular glint changes slowly in wavelength and the diffuse scatter changes quickly with wavelength <i>Examples: car paints and some vegetation in the visible to near IR</i>	Parameterized BRDF at a small number of sparsely spaced wavelengths. High spectral resolution lab measurement of DHR Resulting DHR of model equals lab measured DHR
III	Linear interpolation of both 1 st surface and “bulk” scatter terms of BRDF between reference wavelengths with an additional wavelength dependent gain applied to model such that the resulting hemispherical integration of modeled BRDF matches the lab measured DHR spectrum	Materials for which 1 st surface scatter dominates, but is not the only contributor to the full BRDF magnitude and complex index of refraction values are not known adequately <i>Examples: Painted surfaces in the mid and long wave infrared</i>	Parameterized BRDF at a small number of sparsely spaced wavelengths High spectral resolution lab measurement of DHR Resulting DHR of model equals lab measured DHR

We have also found that no single spectral interpolation approach is best for all materials. In contrast, the optimal spectral interpolation approach is typically both material and wavelength dependent fostering the need for flexibility in this area. In response to these findings, RIT has chosen to support all three variations of spectral interpolation for its generalized microfacet based polarimetric BRDF model utilized in the DIRSIG software.

To further demonstrate the importance of which spectral interpolation approach is used, we show DIRSIG simulation results for three spherical objects (see Figure 3 below). Each of the spheres is attributed with exactly the same material pBRDF parameters at wavelengths of 350nm and 1060 nm. Additionally, each sphere is attributed with the same exact high spectral resolution DHR curve. However the three spheres differ in the spectral interpolation approach for which they utilize for determining the shape of the BRDF between the two reference wavelengths of 350 and 1060 nm. We have deliberately chosen to keep the BRDF parameters at the reference wavelengths the same (implying use of the BRDF parameters without the DHR curve results in a spectrally flat BRDF) in order to demonstrate how the high spectral resolution DHR lab measured curve can significantly drive the objects “color” independent (II) or dependent (III) on the shape of the BRDF measured at the reference wavelengths. Also notable is the spectral color of the glint (and hence the S1 signature) of approaches I and II are spectrally flat while the glint of the sphere utilizing approach III follows the spectral shape of the lab measured DHR curve regardless of the glint magnitude described in the BRDF model at the reference wavelengths alone.

Figure 3. DIRSIG renderings (Stoke’s S₀ and S₁) of three spheres having exactly the pBRDF parameters but using different spectral interpolation approaches.

4. SUITABILITY TESTS FOR SCATTERING AND EMISSION MODELS

For use in our DIRSIG radiative transfer environment, RIT commonly conducts three separate testing methods for evaluating the suitability of specific material properties. In a nutshell, a “well – parameterized” BRDF has the following qualities: (1) a calculated hemispherical integration of the modeled BRDF (before spectral interpolation) at the reference wavelengths agrees with the lab measured DHR curve, (2) the hemispherical integration of the modeled BRDF after spectral interpolation has values between 0 and 1.0, and (3) the total polarization of the Stoke’s emissivity vector is less than or equal to 100%. These three requirements and example testing methods are described below.

4.1. Inspection of BRDF Parameters Relative to DHR Spectrum

Our man-in-the-loop type of material inspection involves hemispherical integration of the BRDF parameters at the reference wavelengths (before spectral interpolation) and comparing the values to the lab measured DHR values. In many cases, we have found this to be the simplest way to discriminate which materials are more likely to behave well and within the bounds of physics and which are likely to violate them under stressing geometric conditions (grazing angles). Additionally, we typically inspect the values of the complex index of refraction model parameters in hopes that they correspond to expected values for one or more of the material’s constituents. This is straightforward for

homogeneous surfaces such as metals where these values are commonly published in CRC handbooks, but can be quite challenging for aggregate materials such as concretes and asphalt.

Figure 4. Examples of agreement (left) and disagreement (right) between goniometer derived DHR (points) and integrating sphere measured DHR (curve).

The two sets of curves in Figure 4 demonstrate notional “white” paint DHR curves measured using an integrating sphere compared with a hemispherical integration of the total amount of light reflected from the same surface measured by a goniometer (used for deriving the BRDF parameters at reference wavelengths). Additionally, we can utilize this agreement or lack of agreement to help decide which spectral interpolation method to employ in the modeling environment. We have not yet found a simple rule of thumb to follow, but the work is ongoing.

4.2. Evaluation of Directional Hemispherical Reflectance of Spectrally Interpolated BRDF Model

Next, we utilize the DIRSIG model to simulate the spectrally interpolated DHR via the concept of reciprocity. More specifically, we illuminate the material surface in DIRSIG with a uniform hemisphere of radiance $1 \text{ W/cm}^2/\text{sr}/\mu\text{m}$ illumination and ‘measure’ the DHR by evaluating the aperture reaching radiance as a function of view angle (representing the incidence angle of DHR since we are leveraging BRDF reciprocity). This concept is illustrated in Figure 5 below.

Figure 5. Cut-away illustration showing light paths in integrating sphere DHR measurement next to illustration of light paths used for DIRSIG evaluation of a material’s modeled DHR.

In practice, we find that performing this virtual DHR evaluation is most efficiently conducted by rendering a spherical object on a perfectly reflecting mirror ground plane. Ideally, each surface of the sphere with a local normal direction pointing towards the some portion of the sky (local zenith angle of normal between 0 and 90 degrees) will see uniform irradiance in the hemisphere above it due to the perfectly reflecting ground plane. To illustrate this concept, we present a few variations on a DHR = 1.0 material, each variation having a different set of BRDF parameters that “nominally” achieve a hemispherical integration value of 1.0.

Figure 6. Examples of virtual DHR evaluation for variations on a DHR = 1.0 (nominally) material. Left to right, the materials are representative of a perfectly Lambertian material, two variations of a glossy white paint, and a near perfect specular Fresnel reflector (mirror surface) where the ground plane gray level corresponds to a virtual DHR measurement of 1.0, dark areas less than 1.0 and whiter areas greater than 1.0.

In some cases, manual modification of the BRDF parameters at the reference wavelengths is required to keep the modeled DHR physically meaningful (less than or equal to 100%). Although the DIRSIG software model has checks in place to prevent negative valued spectrally interpolated BRDF magnitudes, the model relies on the user to correctly configure materials such that the resulting DHR at all angles is less than 100%. For the purposes of calculating emissivity Stoke’s vectors from calculated DHR, the DIRSIG model prevents >100% values (preventing negative emissivity magnitudes).

4.3. Evaluation of Total Polarization of Stoke’s Emissivity Vector

A final test of a specific material’s set of BRDF parameters and associated lab measured directional hemispherical reflectance is an evaluation of the derived polarization state of the spectral emissivity. RIT has found a significant number of materials in community databases that tend to predict a S1 and/or S2 component of the Stoke’s emissivity vector that is actually greater than the S0 component of the emissivity vector. The resulting thermally emitted radiance has a degree of linear polarization greater than 100%, which is quite non-physical.

We have found that in many cases the origin of the non-physical emission polarization signature arises from a non-physical set of BRDF model parameters that might be perfectly valid for many geometries of the BRDF evaluation, but when hemispherically integrated to derive an emissivity vector, the result defies physical boundaries.

In order to detect problems before they manifest themselves in a full radiometric, multi-bounce complex radiative transfer scenario (see bottom row of Figure 7), we typically model the emitted polarimetric signature of a simple shape such as a sphere to probe for problematic signatures (see top row of Figure 7 below).

Figure 7. Illustration demonstrating well behaved material properties in the long wave infrared (top row: degree of linear polarization less than or equal to 1.0) and poorly behaved material properties (bottom row, circled region has degree of linear polarization greater than 1.0 due to poorly configured BRDF parameters).

5. CONCLUSION

In conclusion, we have presented a generalized BRDF model that is flexible for capturing the material reflectance and emissivity properties of a variety of existing materials databases. Additionally we have summarized a total of three different approaches to performing spectral interpolation of this model and emphasized the pros and cons of each relative to what is known about the material and the wavelengths for which the interpolation might occur.

Additionally, we have presented a series of sanity tests RIT typically performs on material properties before utilizing database and lab measured results that are to be used to drive BRDF and emission signature modeling in the DIRSIG model. Future work requires not only defensive type testing of models after the fact, but a deeper look to offensively understand how to better characterize material optical properties in the lab environment before extending them into the virtual modeling world of polarimetric signatures. There are wavelength regions and material types that are well understood and well modeled (see Figure 8 below) and many examples of the opposite case (see many of the preceding figures in this paper). Therefore the important takeaway for us is to continue to critically evaluate material BRDF and emission models well before implementing them into a complex radiative transfer environment where any non-physical scattering and emission mechanisms might not be as apparent.

Figure 8. Examples of a DIRSIG simulations of a ground based polarimetric imager (top row) and airborne based polarimetric imager over a parking lot area.

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