Synthesis and analysis of custom bi-directional reflectivity distribution functions in DIRSIG

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1. ABSTRACT

The bi-directional reflectivity distribution (BRDF) function is a fundamental optical property of materials, characterizing important properties of light scattered by a surface. For accurate radiance calculations using synthetic targets and numerical simulations such as the Digital Imaging and Remote Sensing Image Generation (DIRSIG) model, fidelity of the target BRDFs is critical. While fits to measured BRDF data can be used in DIRSIG, obtaining high-quality data over a large spectral continuum can be time-consuming and expensive, requiring significant investment in illumination sources, sensors, and other specialized hardware. As a consequence, numerous parametric BRDF models are available to approximate actual behavior; but these all have shortcomings. Further, DIRSIG doesn't allow direct visualization of BRDFs, making it difficult for the user to understand the numerical impact of various models. Here, we discuss the innovative use of "mixture maps" to synthesize custom BRDFs as linear combinations of parametric models and measured data. We also show how DIRSIG's interactive mode can be used to visualize and analyze both available parametric models currently used in DIRSIG and custom BRDFs developed using our methods.

2. INTRODUCTION

There is an increasing need for simulated imagery to drive the development of algorithms, train image analysts, and derive requirements for future sensors and missions by estimating what an optical system can detect before they are built. [1] To create useful simulated images under fully-controllable conditions, synthetic targets are required. A number of inputs, such as a model of the illumination source, atmospheric contribution estimates, computer-aided design (CAD) geometry of sufficient resolution, physical attributes to apply to the CAD models, tools to calculate the radiative transfer, and a model of the imaging sensor itself to generate a realistic simulated image. Key data that seem to always be in greater demand than supply for synthetic CAD objects are bi-directional reflectivity distribution functions (BRDF).

The BRDF is what the radiative transfer codes like Digital Imaging and Remote Sensing Image Generation (DIRSIG) need to determine the amount of energy being scattered by the target towards a detector. The current stable release, DIRSIG4.7.1.16605, is run most commonly by executing a master .sim file. This .sim file points to five other files, a .scene, .atm, .platform, .ppd, and a .tasks file. The .scene file points to a .mat file where the BRDF information is set for each object in the synthetic set. DIRSIG's output is an at aperture radiance value. The user has full control over the illumination in the scene and BRDF can be obtained via Eq. 1.

$$BRDF\ [sr^{-1}] = \frac{Radiance\ (DIRSIG\ Image)}{Irradiance} \quad (1)$$

Due to the expenses involved with measuring a fully-sampled BRDF, existing material property databases have numerous deficiencies. Diffuse hemispherical reflectance (DHR) data, on the other hand, is much easier to acquire and therefore much more abundant. The DHR defined as the integral of the BRDF over the 2π sr of the reflection hemisphere:

$$DHR = \int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi/2} BRDF\ cos\theta_r\ sin\theta_r\, d\theta_r\, d\varphi_r \quad (2)$$

In other words, the DHR is the total amount of energy reflected into the hemisphere above a particular facet (sample) for one illumination angle. [2]

The DIRSIG download is accompanied by a number of pre-built and pre-attributed synthetic sets. In Fig. 1. we show a small portion of the Urban scene along with the DHR curves derived from the emissivity data provided for freshly mowed grass. A texture map has been applied to the grass and the trees have been deleted from the synthetic set to highlight the grass for this example. The spectral DHR curves are the only measurements provided to the user. It is often the case that a DHR value is the only reflectance information that is available for a specific material, i.e. no BRDF information is included. The user must then somehow select which of the infinite amount of possible BRDFs to use along with this DHR value.

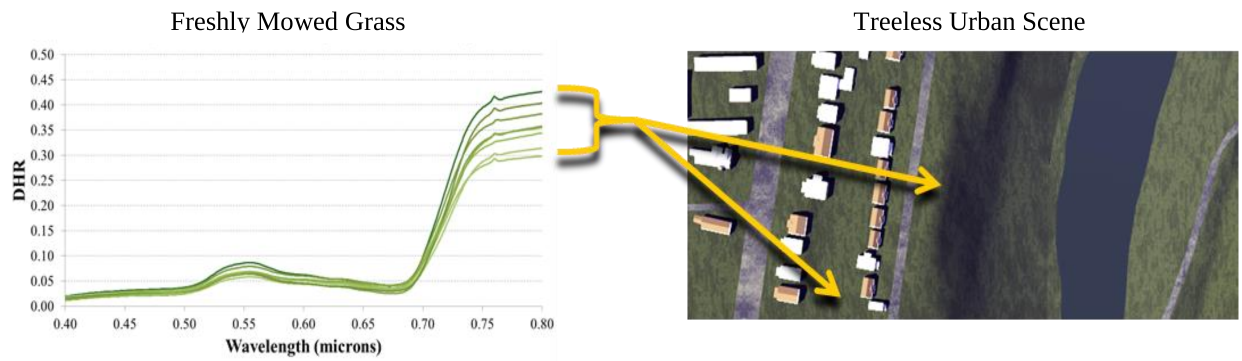

Fig. 1. (left) Example spectral DHR curves derived from a DIRSIG emissivity file.
(right) Grass curves attributed to terrain in DIRSIG's urban scene

We developed a custom "swatch tester" specifically to analyze DIRSIG BRDF renders and inspect the differences between how DIRSIG's radiometry solvers handle of multiple bounces. In Fig. 2. we show this tester attributed with two different BRDFs. Integrating either of the BRDFs in Fig. 2 yields the mean of the DHR curves shown in Fig. 1. As shown by the side-by-side swatches, the photocount in any particular simulated image pixel can differ dramatically under identical illumination conditions depending on the user's choice of BRDF. If both BRDF and DHR measurements are available, it's up to the user to make sure the measured BRDF matches the measured DHR. If they do not match, the user must reconcile the difference using whatever ancillary data or knowledge is at hand.

DIRSIG allows the user to input the BRDF through a number of different parametric models including: NEF Beard-Maxwell, Phong, Shell Target, Ward, etc. All of the models, no matter how well they reproduce measurements for some angular domain, can either be misrepresented in the.mat file or have a domain of arguments for which the DHR is outside the range 0 to 1. A number of examples of how many parameters there are for the user to introduce error within specific BRDF models can be found in Dr. Michael Gartley's Ph.D. dissertation. [3] We want DIRSIG users to be confident that they are applying a physically plausible material to all of the facets in their synthetic set no matter what BRDF model they choose. If the user can at least demonstrate the BRDF matches the DHR, it becomes easier to justify the use of a particular BRDF model and model parameters. Combining precise placement of DIRSIG's rays along with the ability to use more than one BRDF model on any given facet we will show how DIRSIG can be used to not only check that the BRDF model matches the DHR, but also gives the user a way to increase the success of matching lab measured BRDF data.

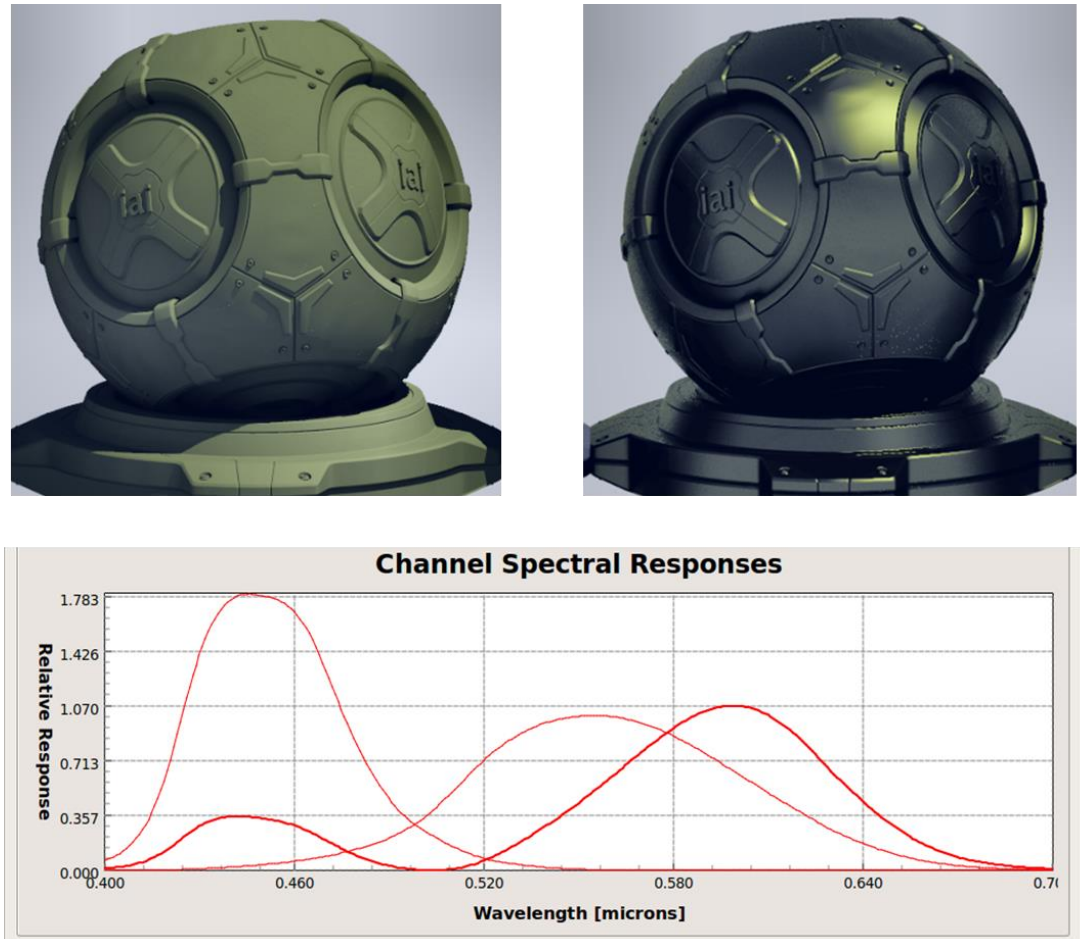

Fig. 2. Freshly mowed grass BRDF analysis via “swatch testers:” (Top left) perfectly diffuse (Top right) specular via Maxwell-Beard .fit file (Bottom) DIRSIG3 built in CIE-XYZ response

3. FLAT PLATE ANALYSIS

A theoretical perfect mirror will have a BRDF of ∞ sr^{-1} exactly at the specular reflection direction and 0 sr^{-1} at all other angles. An ideal diffuse reflector will have a BRDF of 1/π for all reflection angles. A specular sweep scenario has been set up with a flat plate that a BRDF can be applied to via the .mat file. Directly above this flat plate are an illumination source, the sun set at a spectrally constant irradiance of $1\frac{W}{cm^2}$ and a sensor that will remain fixed in place. The atmospheric contribution has been set to zero using the uniform atmosphere via the .atm file. The facet will start with a -10^0 rotation along a single axis so that the specular reflection is 20^0 away from the sensor. The plate is then continuously rotated until the specular reflection is at 160^0 on the opposite side of the camera. The specular sweep simulation is a way to quickly check for unexpected behavior of the BRDF supplied in the .mat entry. Some BRDF models incorporate a Fresnel term that can mimic the increased reflectance at high grazing angles.[4] This simple simulation can be used to analyze the peak specular BRDF value, the specular lobe-width, and the glancing angle returns can be examined for any unexpected behaviors.

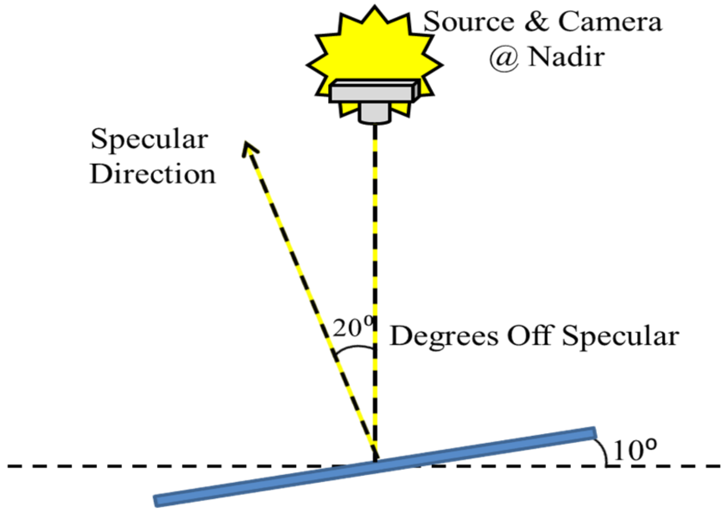

Fig. 3. Set up of simple DIRSIG scene to analyze BRDF properties on a rotating flat plate. The plate rotates so that the specular direction goes from 20^0 on the left of the camera to 160^0 on the right

A 1-D examination of the specular sweep simulations run with 4 different materials is shown in Fig. 4. This scenario only requires one ray, or pixel, to be cast towards the plate per rotation angle of the plate. This analysis just reveals a slice view of a full BRDF of a material. To get a 2D view of the BRDF and do some more thorough error checking DIRSIG's interactive mode can be used. This mode can sample the synthetic set one ray at a time from any location and in any direction that the user desires. We will show how to take advantage of this mode in order to reduce the sources of error found in user input of parameters to a BRDF model and in the chance that a particular BRDF model may not even be implemented properly in the code itself.

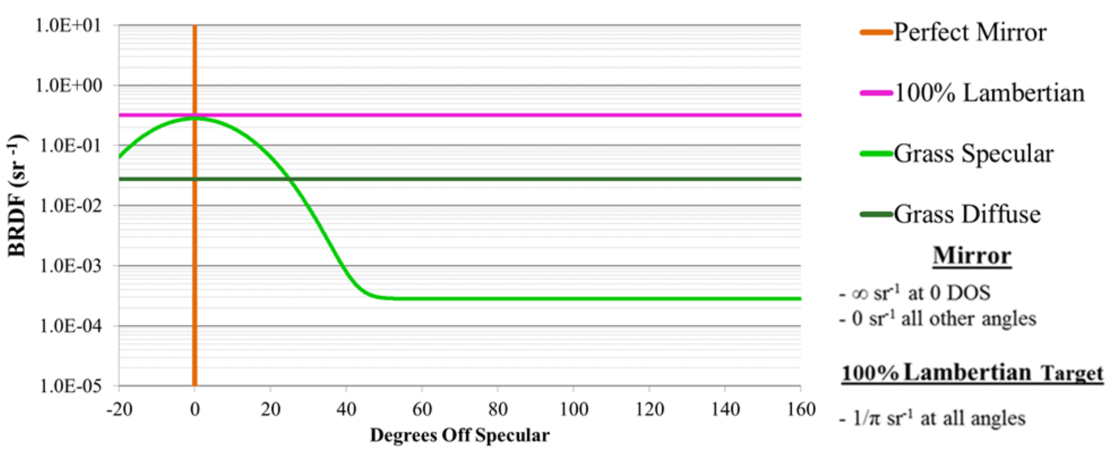

Fig. 4. Sweep analysis of ideal target samples and the two variations of freshly mowed grass BRDF

4. INTERACTIVE MODE

DIRSIG is introduced to new users by having them set up focal planes that have an x and y dimension i.e. 512x512 pixels with 20 micron size and no gaps. Interactive mode allows the user to pre-load the whole scene and have DIRSIG wait for user provided locations and directions for the rays to be cast out to sample the synthetic set. One can use this for debugging purposes to not only get at aperture reading radiance, but other truth info such as material IDs, temperature, and transmission as well. The user is not limited to hand inputting rays one by one, a list of locations and pointing directions can be sent at once via a text file. The traditional flat x/y focal planes are not required in this mode as it is with the gui, the list of locations and pointing directions for the rays can be completely arbitrary if one wishes.

To get a 2-D view of a BRDF, a list of rays have been arranged in a dome over a facet that lies at the bottom center, which can be sent to DIRSIG via a text file. Each of these rays will then be cast out toward the facet to get a value for the aperture reaching radiance. Using Eq. 1. BRDF can now be solved for at each ray location. Since the atmospheric radiance contribution has been set to 0, the DIRSIG output of at aperture radiance value is all the information needed to estimate the DHR integral in Eq. 2. If the user only has access to DHR data, then this method can be used to ensure that BRDF parameterization they choose will match the DHR measurement. If it does not,

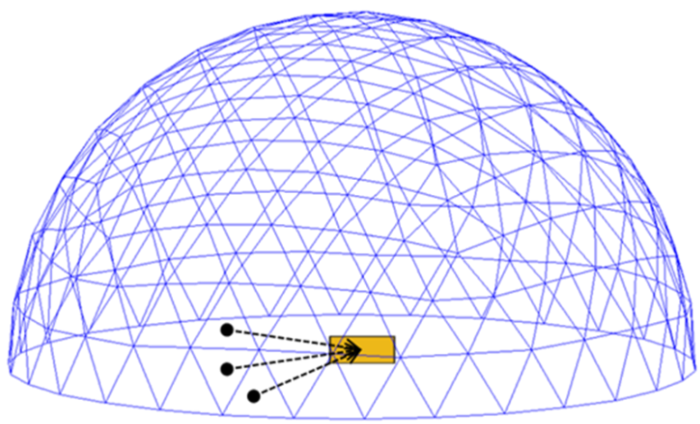

Fig. 5. Visualization of interactive dome created by ray locations and directions for viewing of a facet and estimation of the DHR integral

then the parameters of that BRDF model must be changed until that model matches the measured data. A 2-D representation of the specular grass material for two different illumination angles is shown in Fig. 6. as seen from the interactive dome.

The mean of the emissivity curves found in the freshly mowed grass .ems library of the DIRSIG urban scene was used to obtain a set of Shell target model BRDF parameters that would match the DHR for the mean curve. The mean emissivity value at 0.45 um is 0.975390375. Assuming there are no losses due to transmission, the mean DHR is 0.024609625. With a 0.5° delta of rays sent via interactive mode, the DHR estimate at 0.45 um is 0.0246058609345.

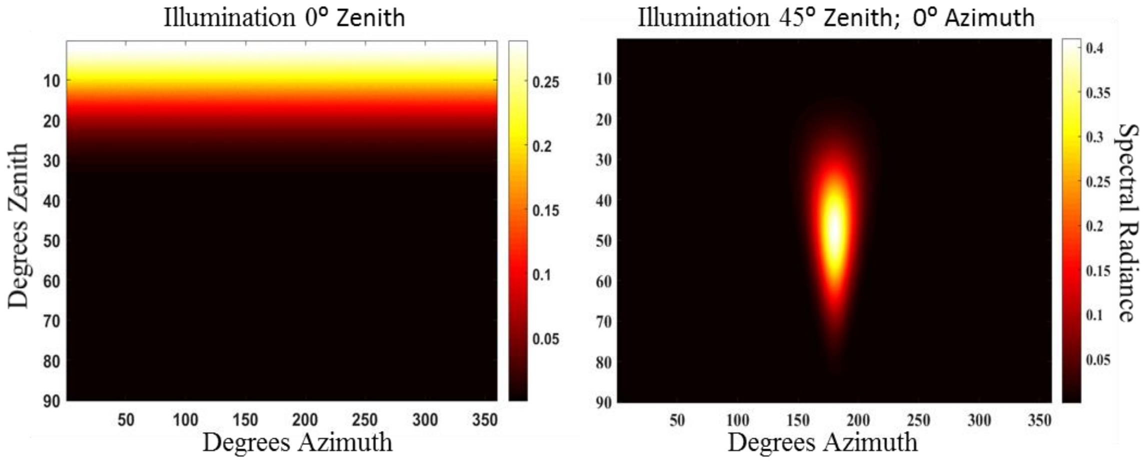

Fig. 6. Spectral radiance from the interactive dome pixels

5. MIXTURE MAPS

Originally developed for use in DIRSIG, mixture maps allow a single spatial coordinate in the set to be associated with the properties of multiple materials; an easily-understood example is grass distributed in soil with varying densities. We have exploited mixture maps to create linear combinations of parametric BRDF models to facilitate better matches with available data. When a mixture map is enabled, it is telling DIRSIG to compute the full radiometric solution for a given ray multiple times. If the user wants to mix two different materials, DIRSIG will cast a ray out from the same location and in the same direction twice, and will compute the full at aperture radiance calculation twice. Different materials may have vastly different thermal and optical properties, so a full solution must be calculated before weighting the radiance values. The individual materials being mixed do not necessarily need to conserve energy, however the final mixed material should.

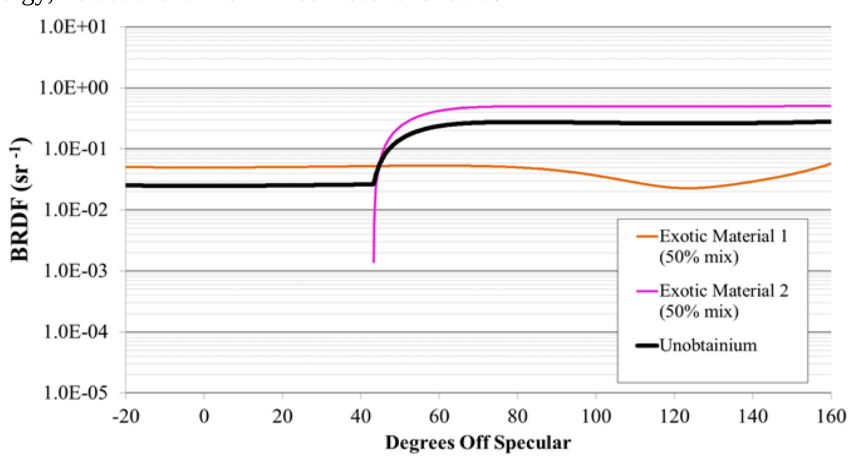

Fig. 7. Sweep analysis of individual components (orange and pink) and final mixed material (black)

A specular sweep of a simple 50/50 mixture map can be found in Fig. 7.We have forced one material to have material properties that result in a zero radiance return for angles shallower than 40^0 off specular. This material was mixed with a mostly diffuse material with a tiny dip in signature around 120^0 off specular. The resulting material is "unobtainium", a material that will return more radiance at higher degrees off specular than it will for a direct glint angle. In Fig. 8. the dark anti-glint can be easily seen where there is usually a bright return as in the gloss grass from Fig. 2.

Fig. 8. Swatch analysis of the mixture map material of unobtainium. The dark spot is the anti-glint area where a strong return would normally be from a glossy material

6. CONCLUSION

BRDFs are critical to obtaining correct radiometry from synthetic sets in DIRSIG. While BRDF phase functions are not directly observable to the DIRSIG user, we have provided two ways – the “flat-plate sweep” test and a dome of “interactive mode” pixels – to visualize the phase function for any particular BRDF model and parameters. The pixel dome also allows the user to approximate a numerical integration of the BRDF to check correspondence with the associated DHR. Finally, we discuss the use of mixture maps to model BRDFs as linear combinations of parametric models and measured data. Mixture maps allow for greater flexibility matching lab measured data and potentially advanced material analysis. The methods that have been discussed can reduce some human error in the formation of simulated imagery resulting in higher quality data for algorithms to be developed against or for requirements to be determined.

7. Acknowledgements

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8. REFERENCES

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