MODELING VISIBLE/NEAR-INFRARED PHOTOMETRIC PROPERTIES OF DUSTFALL ON A KNOWN SUBSTRATE.

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Introduction: We present a comprehensive visible/near-infrared two-layer radiative transfer modeling study using laboratory spectra of variable dust thicknesses deposited on substrates with known photometric parameters. The masking effects of Martian airfall dust deposition on rocks, soils, and lander/rover components provides the incentive to improve two-layer models [1-3]. It is believed that the model presented will facilitate understanding of the spectral and compositional properties of both the dust layer and substrate material, and allow for better compensation for dust deposition.

Model: We have implemented an adaptation of the Hapke model of bidirectional reflectance of a two-layer medium ([4] p. 251). This adapted model allows the particulate lower layer in the two-layer model to be replaced with an arbitrary substrate defined only by its Bidirectional Reflectance Distribution Function (BRDF). The freedom of definition for the substrate material allows for the accurate modeling of dust accumulation on non-Hapke materials (e.g., rocks with a strong specular scattering lobe, silicone rubber RTV used in calibration targets).

This adaptation of the Hapke two-layer model consists of the substitution of the substrate's single particle angular scattering function $p_L(g)$, which depends only on phase angle and is meaningful only in the context of particulate media, with an analogous bidirectional scattering function $q_L(z,el,az',el')$, where az,el define the incident vector, and az',el' define the emission vector. This bidirectional scattering function (q) is defined as:

$$q(az,el,az',el') = \pi \cdot BRDF(az,el,az',el') / r_s$$

where r_S is the spherical reflectance. In practice, the spherical reflectance is frequently unknown, and normalization of q is performed by numerical integration of the BRDF.

The bidirectional scattering function (q) simplifies to the single particle angular scattering function (p) in the case of a Lambertian substrate. In addition the bidirectional scattering function fulfills an analogue of the single particle angular scattering function's normalization constraint:

$$\int_{2\pi}\int_{2\pi} q(az,el,az',el')\,d\Omega\,d\Omega' = (2\pi)^2$$

The Hapke two-layer model also depends on the substrate albedo factor (g_L). Although g_L can in theory be derived from the BRDF$^{\perp}$, concern over error implicit in the calculation of r_0 from r_S and over the potentially magnified effect of errors in the substrate BRDF led us to numerically fit rather than analytically solve for g_L.

The specific substrate model used was that developed by the Mars Exploration Rover (MER) Panoramic Camera team to describe the Panoramic Camera Radiometric Calibration Target (RCT) [6]. This model consists of the He-Torrance model [5] - a physical optics model borrowed from the realm of computer science - combined with a Hapke backscatter term [4]. A three-parameter Henyey-Greenstein function was used to fit the upper layer (dust) phase function.

Data: The Bloomsburg University Goniometer (BUG) was used to acquire bidirectional reflectances of the MER Pancam RCT materials (silicone rubber RTV surfaces with approximately 20%, 40%, and 60% reflectances in the visible/near-infrared) at four wavelengths (480, 600, 750, and 930 nm). Measurements also were acquired with variable mean thicknesses (0 to 225 μm) of Mars analog JSC-1 dust deposited on these substrates using an airfall settling technique [7].

Procedure: The bidirectional two-layer reflectance model was fit to the entire data set using a Levenberg-Marquardt least-squares minimization routine with numerically calculated derivatives.

The numerical integration of the substrate models for purposes of normalizing q_L was restricted to 30-50° elevation for the emission vector and 20-90° elevation for the incidence vector. This prevented poor characterization of the RCT BRDF for vectors well outside those acquired using the BUG from negatively impacting the performance of the two-layer model.

Results/Discussion: The model fit the data with a reduced chi-square of 9.1 when the BUG data was assumed to possess a relative error of 5%. The efficacy of this fit can be visually judged in Figures 1

$^{\perp}$ Spherical reflectance (r_S) can be calculated directly from the BRDF, diffusive reflectance (r_0) can be calculated from r_S ([4] p. 269), the volume single scattering albedo (w_L) can be calculated from r_0 ([4] p. 291), and the albedo factor (g_L) is defined in terms of w_L.

Name	Substrate	Thickness	Wavelength	Value
Pu0	---------	------	480 nm	0.16534794
Pu0	---------	------	600 nm	0.054071909
Pu0	---------	------	750 nm	0.033830598
Pu0	---------	------	930 nm	0.042430620
Pu1	---------	------	480 nm	-0.75249348
Pu1	---------	------	600 nm	-0.84302023
Pu1	---------	------	750 nm	-0.86707857
Pu1	---------	------	930 nm	-0.87971395
Pu2	---------	------	480 nm	0.97656175
Pu2	---------	------	600 nm	0.99224375
Pu2	---------	------	750 nm	0.99538410
Pu2	---------	------	930 nm	0.99653797
tau	---------	0 um	------	9.99999e-05
tau	---------	5 um	------	9.99999e-05
tau	---------	10 um	------	0.008792356
tau	---------	24 um	------	0.038402812
tau	---------	45 um	------	0.31140855
tau	---------	132 um	------	1.1573110
tau	---------	225 um	------	1.3772483
wl	black	------	480 nm	0.59818068
wl	black	------	600 nm	0.55086283
wl	black	------	750 nm	0.48988512
wl	black	------	930 nm	0.43596463
wl	gray	------	480 nm	0.83078440
wl	gray	------	600 nm	0.84260554
wl	gray	------	750 nm	0.79792799
wl	gray	------	930 nm	0.74477210
wl	white	------	480 nm	0.88270952
wl	white	------	600 nm	0.91779216
wl	white	------	750 nm	0.89677571
wl	white	------	930 nm	0.88219746
wu	---------	------	480 nm	0.49142599
wu	---------	------	600 nm	0.85253148
wu	---------	------	750 nm	0.96346270
wu	---------	------	930 nm	0.96832510

Table 1 – Parameters fit by the model and their associated values. Where parameters depend on substrate material, dust thickness, or filter wavelength that information is also provided. *Pu0*, *Pu1*, and *Pu2* are respectively the forward asymmetry, backward asymmetry, and forward fraction parameters for the upper layer three-parameter Henyey-Greenstein phase function. *tau* is the dust opacity, and *wu* and *wl* are the single scattering albedos of the upper and lower layer, respectively. It should be noted that the near unity forward fractions (*Pu2*) make the large backward asymmetry parameters (*Pu1*) nearly meaningless, as the backward lobe of the upper layer phase function is nearly nonexistent.

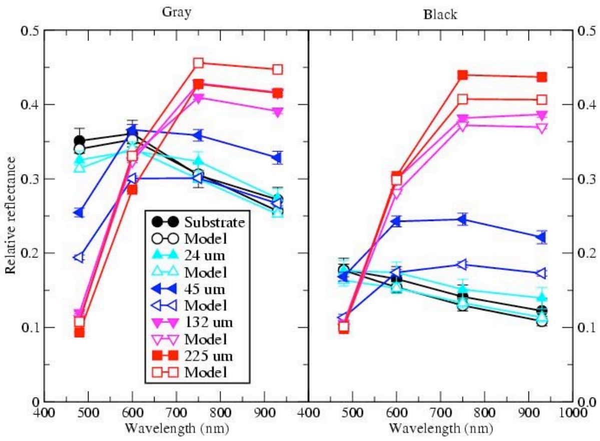

Figure 2 – Measured (closed symbols) and modeled (open symbols) spectra for several dust thickness for gray (40%) and black (20%) substrates.

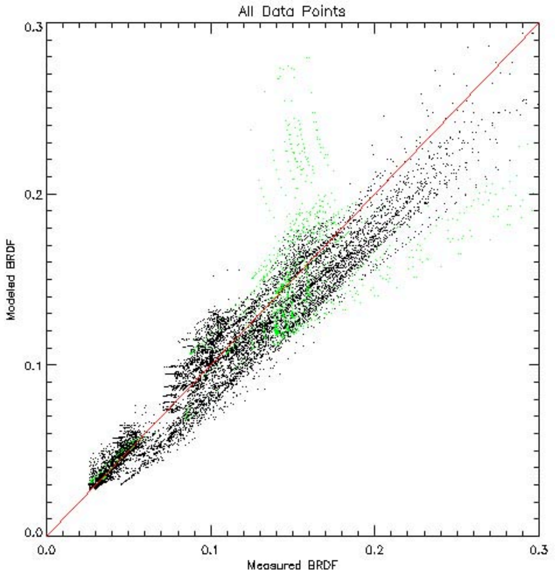

Figure 1 – Scatter plot of measured vs. fit BRDF values for all substrates, dust thicknesses, and geometries. Red line is 1:1 correlation line. Data points from the white (60%) substrate are highlighted green. Data collection was hampered for the white substrate due to the small size of the available silicone RTV sample.

and 2, which show a scatter plot of measured vs. modeled data, and plots of measured and modeled spectra (BRDF * π) for different substrates and dust thicknesses respectively.

The data acquired of the white (60% reflective) RCT substrate is marked green in Figure 1. The deviation of these measured values from the model is consistent with a known data acquisition problem relating to the size of the white silicone RTV sample. Indeed, when the fit is run without the white substrate data the reduced chi-square takes on the improved value of 7.6.

The parameter values fit by the model (see Table 1) show physically realistic trends. Fitted optical depth tau correlates well with measured coating thickness, and derived single particle phase functions for the dust are nearly isotropic. Derived dust single scattering albedos exhibit the expected red slope. Figure 2 shows that the model does a good job of matching the spectral evolution of the surface as more dust is deposited, with the gray and black substrates being progressively darkened at blue wavelengths, and progressively brightened at red wavelengths.

References: [1] Johnson, J.R., and W.M. Grundy, *Geophys. Res. Lett.*, 28, 2101-2104, 2001; [2] Johnson, J.R., et al. *Icarus*, 163, 330-346, 2003; [3] Johnson, J.R., et al. *Icarus*, 171, 546-556, 2004; [4] Hapke, B., Cambridge University Press, 455 pp., 1993; [5] He, X.D, and Torrance, K.E., *Computer Graphics*, 25, 175-186, 1991.; [6] Bell III, J.F. et al., *JGR, 108*, 2003, 10.1029/2003JE002070; [7] Graff et al., *LPSC XXXII*, abstract 1899, 2001; [8] M.K. Shepard, *LPSC XXXII*, abstract 1015, 2001;