Surface scattering properties at the Opportunity Mars rover’s traverse region measured by CRISM

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[1] The Opportunity Rover has been exploring Meridiani Planum; concurrently, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) has been collecting orbital hyperspectral data. Herein, both surface and orbital data are used to characterize surface properties at the Opportunity traverse region around Victoria crater. Results agree with previous studies, which used Opportunity’s Panoramic Camera (Pancam) data, and the current study extends estimates of the Hapke single-particle-scattering albedo and asymmetry parameter to a greater spatial and spectral range. Results are useful for determining boundaries between surface units that otherwise look relatively uniform spectrally. This work also provides photometric functions essential for converting spectra to a single viewing geometry to yield more accurate spectral comparisons. Retrieved single-scattering albedos range from 0.42 to 0.57 (0.5663–2.2715 micrometers) and retrieved asymmetry parameters range from −0.27 to −0.17 (moderately backscattering). Surfaces become more backscattering with increasing wavelength above 1 μm. The majority of Victoria crater’s ejecta apron is more backscattering than surrounding regions, indicating a change in physical properties. Images taken when the rover traversed this unit show a cover of basaltic soil with superposed millimeter-scale hematitic spherules. Wind streaks on the apron appear smooth (low backscatter) because basaltic sands have partly buried spherules, lessening millimeter-scale roughness. CRISM-derived scattering parameters also show that bedrock-dominated surfaces are less backscattering than soil-covered surfaces, largely due to lower areal abundance of spherules. The ability to analyze surface unit spherule cover is important because it relates to a wetter period during which spherules formed in Meridiani.


1. Introduction

[2] This paper consists of two halves, the first of which focuses on the use of Mars Reconnaissance Orbiter (MRO)’s CRISM spectrophotometric data coupled with surface observations from the Opportunity rover in order to derive surface scattering properties for Victoria crater’s ejecta apron and its surroundings. The region around Victoria crater was chosen for this investigation because it has the highest quality spectrophotometric coverage, and this coverage was acquired because this region has a variety of geologic features and diverse terrain. The second half of the paper focuses on the interpretation of the scattering properties in terms of surface characteristics.

[3] First, an overview of the region traversed by the Opportunity rover is given, paying particular attention to the area around Victoria, a large crater visited by the rover, over which a particularly high-quality CRISM observation was acquired. Next, the CRISM data set is described in detail and its suitability for analysis of scattering properties is discussed. Following the dataset description, an in-depth treatment of the modeling process is provided; this treatment is divided into three parts: (1) the surface model that is used in this work is introduced, (2) the atmospheric model is outlined, and (3) the simultaneous implementation of both models in combination with the CRISM dataset is addressed. Next, the scattering parameter results are described and then compared to the results of previous workers who have spectrophotometrically analyzed the near-surface data provided by Opportunity. Lastly, the results presented in this paper are interpreted in terms of surface roughness, and it is shown that while large-scale roughness in the form of ripples does not affect backscatter, small-scale roughness in the form of hematite-rich spherules dominates the observed backscatter patterns.

2. Background

[4] The investigation of surface scattering properties presented in this paper is focused on the region where the
operational (at time of publication) Opportunity Mars rover is located. Opportunity’s landing site is relatively close to the equator (1.95°S, 354.47°E), in a region called Meridiani Planum, which is Noachian or Early Hesperian in age based on crater-counting statistics [Arvidson et al., 2006]. For an overview of the Opportunity mission and results, see Arvidson et al. [2011] and Squyres et al. [2006a, 2006b]. For previous studies of surface scattering properties in Meridiani Planum, see Johnson et al. [2006a, 2006b], Geissler et al. [2008], and Fernando et al. [2013].

The region around the traverse consists of variable thicknesses of soil over bedrock, with bedrock exposed in some regions (based on images from the High Resolution Imaging Science Experiment (HiRISE on MRO), the Context Camera (CTX on MRO), and Pancam). Soil consists of basaltic grains, dust, and hematite (Fe₂O₃)-rich spherules (lower limit 24% hematite [Morris et al., 2006]). Other workers have discussed the history of water in this region, so only a few brief points are mentioned here. Andrews-Hanna et al. [2007] showed that the original deposits in Meridiani likely formed from groundwater upwelling and subsequent evaporation which left behind layered sulfate-rich sediment. Hematite-rich spherules are present in the region and indicate diageneosis via liquid water [Squyres et al., 2006a, 2006b]. Additionally, the presence of sulfate-rich cross-laminated bedrock is evidence for rock formation in flowing water [Squyres et al., 2004a, 2004b, 2006a, 2006b].

A significant portion of the rover’s 35.4 km traverse (as of 15 November 2012) occurred over a high-elevation (generally 10–15 m above surrounding terrain) aeolian ripple-rich semitriangular feature located northwest of the 22 km wide Endeavour crater (Figure 1; as of 15 November 2012, the Opportunity rover is located on the rim of Endeavour). This semitriangular feature has wider ripples and lower thermal inertia (Figure 2) than surrounding areas, with the exception of similarly heavily rippled, low thermal inertia areas that comprise the wind streaks extending from small nearby craters (Figure 3). The lower thermal inertia of the semitriangular region indicates that the material within the top few centimeters of the semitriangular feature has a smaller particle size and/or is less indurated than surrounding surfaces [Mellon et al., 2000]. In Figure 2, the visible portion of the semitriangular region has been outlined. Note that this most densely rippled area occurs within the low thermal inertia region. The ripple maps in Figures 2 and 3 were generated from images from HiRISE using a terrain classifier developed by Yasuhiro Katayama and run by Paolo Bellutta at NASA’s Jet Propulsion Laboratory. For a description of the ripple map generation using a machine vision algorithm involving image segmentation through pattern (texture) recognition, see Golombek et al. [2012]. The algorithm identifies features and uses their spatial distribution, size, and alignment to classify terrain. Thermal inertia information was derived by Michael Mellon using data from the Thermal Emission Imaging System (THEMIS) onboard the Mars Odyssey (ODY) spacecraft.

The Opportunity rover spent considerable time around Victoria crater (Figure 4) [Squyres et al., 2006b]. At about 750 m in diameter and about 75 m deep [Grant et al., 2008], Victoria is the second largest crater visited by the rover, and it was the largest at the time FRT0000B6B5 was acquired. Likely, when Victoria formed, it was ~600 m in diameter and ~125 m deep [Grant et al., 2008]. Victoria crater has several wind streaks emanating from the northern and eastern sections of its rim, and observations from the Opportunity rover indicate that the streaks consist in large part of basaltic sand that had been trapped in the crater and subsequently blown out in streaks [Geissler et al., 2008]. The relatively soft sulfate-rich ejecta blocks have been eroded to the level of the surrounding surface and are visible only near the inner edge of the 4–5 m high, 120–200 m wide rim and the top of the crater walls [Squyres et al., 2009; Arvidson et al., 2011].
3. Primary Data Sets

CRISM [Murchie et al., 2007] measures the radiance of the surface of Mars as seen through its atmosphere. CRISM has several types of observation modes; the most useful for surface photometry is the FRT or Full Resolution Targeted mode, which has the maximum phase angle coverage (the phase angle is the angle between the incident and emergent directions). A schematic of the acquisition of CRISM FRTs is shown in Figure 5 (see Murchie et al. [2006] for more information). CRISM collects data as it flies from south to north, the black arrow in the figure show this flight path. While collecting data, CRISM gimbals, which means that it alters its viewing angle to track a target patch of ground as it flies over, allowing the measurement of light that the target has scattered to different directions and therefore the determination of how the scattering of light varies with phase angle.

There are 11 images associated with an FRT collected during nominal gimbal operation; five of which (labeled 01 to 05 in CRISM product files) are acquired at discrete viewing geometries as MRO flies toward a target (see Figure 5), one of which (labeled 07) is acquired as a near-nadir scan with continuously varying viewing geometry, and the last five images (labeled 09 to 0D) are acquired at discrete viewing geometries as MRO flies away from the target. Geometry products are available for each of the 11 images; these products give incidence, emergence, and phase angles for every pixel (this information is derived from several SPICE kernels). For the emergence, phase, and incidence angle coverage of each image in FRT0000B6B5, see Table 1. The images in an FRT vary in spatial resolution because they are taken at varying distances from the target. The central scan has the highest spatial resolution at ~15–20 m/pixel (see Table 2 for information specific to FRT0000B6B5). The first and last images of the sequence have the largest pixel sizes, at about 350–400 m/pixel. For ease of analysis (i.e., to enable phase function extraction via ENVI Environment for Visualizing Images and the IDL Interactive Data Language programming environment and to result in quicker computation times), all images were resampled to seven times the resolution of the central scan.

All 11 images in an FRT are hyperspectral in nature, which means they use all of CRISM’s available channels (536 bands from 0.365 to 3.937 μm, split across two detectors called “S” for short wavelength and “L” for long wavelength). The images result from the readout of detectors which are 640 columns wide in the cross-track direction, and each element in a column corresponds to a separate band (channel) in wavelength space. Motion of the sensor along track achieves the second spatial dimension of each image.

For this work, a subset of six spectral bands was used: 0.566, 0.801, 0.951, 1.277, 1.513, and 2.271 μm. These bands are well spaced to cover much of CRISM’s spectral range and are outside of atmospheric gas (CO2, CO, and H2O) absorption bands. This selection of bands reduces computation time and potential sources of error. Note that atmospheric modeling is still performed in order to account for light scattering from and absorption by aerosols (especially important for wavelengths shorter than 0.7 μm, where aerosol iron mineralogy has a significant effect). Also note that the wavelengths used are in a region of the spectrum in which solar radiation is the dominant factor affecting the signal (i.e., surface blackbody radiation thermal effects do not become an issue until wavelengths greater than 3 μm).

Several FRT observations have been acquired around Opportunity’s traverse area; the FRT used in this work was FRT0000B6B5 (Figure 1; Table 2) because a substantial...
surface area was covered by all 11 images in the observation (i.e., the most phase angle information for the largest region), and it was taken during a period of low atmospheric opacity. When this image was acquired, sunlight was incident from an azimuth of 212.167° clockwise from the east (so approximately from the northwest). For this analysis, the input data is the CRISM standard I/F product (TRR3 version, which is the latest at the time of writing and includes improved noise correction compared to the older version: TRR2). The quantity contained in the CRISM I/F product is radiance at sensor (I) normalized by \( F = I / \pi \), where \( I \) is the incident irradiance. \( I/F \) is equivalent to the radiance factor \( r_f = I / I_0 \), where \( I_0 \) is the radiance that would be observed if the same incoming solar irradiance was normally incident on and scattered by a Lambertian surface.

3.1. Modeling Atmospheric and Surface Radiance Contributions: The Surface Model

[11] To model light scattering from the surface, a simplified version of the Hapke model (equations (1)–(3)) [Hapke, 1993] was used in order to minimize the number of parameters being fitted, so well-constrained fits are obtained over most of the study area.

\[
rf = \left( \frac{w}{4} \right) \left( \frac{\mu_0}{\mu_0 + \mu} \right) [p(g) + H(\mu)H(\mu) - 1] \\
p(g) = \frac{1 - b^2}{[1 + b^2 + 2b\cos(g)]^{3/2}} \\
H(\mu) = \frac{1 + 2\mu}{1 + 2\sqrt{1 - w\mu}}
\]

where \( r_f \) is radiance factor, \( p(g) \) is the average one-term Heney-Greenstein single-particle phase function (note that although \( p(g) \) is intended to describe scattering from a single particle, it will be used here as a more general parameterization of the surface, including any surface properties such as surface roughness, particle packing, etc.), \( g \) is the phase angle, \( w \) is the average single-particle scattering albedo (an indicator of surface reflectivity, this parameter is the ratio of the scattering efficiency to the sum of the scattering and absorption efficiencies and therefore ranges from 0 to 1), \( H \) is the multiple-scattering function, \( \mu_0 \) is the cosine of the incidence angle, \( \mu \) is the cosine of the emergence angle, and \( b \) is the asymmetry parameter. \( b \) varies from \(-1\) to \(1\) and describes how asymmetrically the surface is scattering the incoming light; negative values indicate a backward-scattering surface and positive values indicate a forward-scattering surface. Note that this convention is very different from the one used for the asymmetry parameter for the two-term Heney-Greenstein phase function, where \( b \) describes the directivity, or width, of the scattering lobes and ranges from 0 to 1 in value. Also note that it is not possible to constrain the two-term Heney-Greenstein phase function with only 11 viewing geometries ranging from about 40° to slightly over 100° in phase angle. This parameterization was attempted first, but the global minimum in \( \chi^2 \) space was at the edge of the parameter space, indicating a solution not sufficiently constrained, likely because input data covers a third of the phase space.

[14] The version of the Hapke model used here is basically a radiative transfer model for particulate surfaces that includes the effects of multiple scattering (through the H function shown in equation (3)), and it is used in conjunction with other models for atmospheric effects, such as aerosol scattering and absorption.

Table 1. Emergence, Phase, and Incidence Angle Coverage for Each Image in FRT0000B6B5*

<table>
<thead>
<tr>
<th>FRT Image Segment</th>
<th>Emergence Angle Coverage (°)</th>
<th>Phase Angle Coverage (°)</th>
<th>Incidence Angle Coverage (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>68.1–68.5</td>
<td>105.6–106.5</td>
<td>55.6–56.0</td>
</tr>
<tr>
<td>02</td>
<td>61.4–61.6</td>
<td>100.6–101.4</td>
<td>55.8–56.1</td>
</tr>
<tr>
<td>03</td>
<td>54.7–55.4</td>
<td>95.4–96.8</td>
<td>55.9–56.2</td>
</tr>
<tr>
<td>04</td>
<td>58.3–48.8</td>
<td>90.5–91.8</td>
<td>56.0–56.2</td>
</tr>
<tr>
<td>05</td>
<td>41.9–43.5</td>
<td>85.5–87.6</td>
<td>56.0–56.2</td>
</tr>
<tr>
<td>07</td>
<td>0.1–21.3</td>
<td>43.9–65.9</td>
<td>56.2–56.6</td>
</tr>
<tr>
<td>09</td>
<td>44.8–46.1</td>
<td>39.2–40.9</td>
<td>56.5–56.7</td>
</tr>
<tr>
<td>0A</td>
<td>50.9–51.3</td>
<td>39.9–41.4</td>
<td>56.6–56.9</td>
</tr>
<tr>
<td>0B</td>
<td>56.6–57.4</td>
<td>41.2–42.6</td>
<td>56.6–56.9</td>
</tr>
<tr>
<td>0C</td>
<td>~63.1</td>
<td>43.4–44.5</td>
<td>56.7–57.0</td>
</tr>
<tr>
<td>0D</td>
<td>69.4–69.9</td>
<td>46.2–47.2</td>
<td>56.7–57.2</td>
</tr>
</tbody>
</table>

*Ranges given are for the region where all 11 image segments overlap.
Table 2. Observation Information for FRT0000B6B5a

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for FRT B6B5</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_s (°)</td>
<td>96b</td>
</tr>
<tr>
<td>Mars year</td>
<td>29</td>
</tr>
<tr>
<td>Date of acquisition (MM/DD/YY)</td>
<td>07/08/08</td>
</tr>
<tr>
<td>DOY</td>
<td>190</td>
</tr>
<tr>
<td>Latitude (°N)</td>
<td>-2.05656</td>
</tr>
<tr>
<td>Longitude (°W)</td>
<td>5.48452</td>
</tr>
<tr>
<td>Local time (hours:minutes)</td>
<td>15:24</td>
</tr>
<tr>
<td>Phase angle coverage (°)</td>
<td>39.18–106.48</td>
</tr>
<tr>
<td>Resolution of image 01 (m/pixel)</td>
<td>371.4</td>
</tr>
<tr>
<td>Resolution of central scan (m/pixel)</td>
<td>17.9</td>
</tr>
<tr>
<td>Resolution of image 0D (m/pixel)</td>
<td>391.4</td>
</tr>
</tbody>
</table>

aThe given latitude and longitude are for the spatial center of the FRT’s high-resolution central scan.
bThis solar longitude corresponds to just after the middle of winter in the southern hemisphere.

with the one-term Henyey-Greenstein phase function. Inputs at each iteration include the radiance at the surface and the illumination and viewing geometry, and the parameters being fit for are w (which is independent of illumination and viewing geometry) and b (describes the degree to which the phase function is anisotropic) for each 11 frame deep pixel (i.e., for 11 different combinations of emergence angle, phase angle, and I/F). Note that the simplified version of the Hapke model used here does not have surface roughness as a separate parameter; therefore, the effects of surface roughness are included in and end up dominating the expression of b, allowing the generation of maps of surface roughness (this interpretation is backed by comparisons to studies using near-surface data and laboratory experiments). In contrast to other versions of the Hapke Model, no constraints are imposed on the symmetry of the roughness elements. Also note that in equation (1), the opposition effect is not modeled since this effect is only important at smaller phase angles, and the phase coverage of FRT0000B6B5 does not extend below 39° (see Table 2).

3.2. Modeling Atmospheric and Surface Radiance Contributions: The Atmospheric Model

[15] To model the atmosphere, Discrete Ordinate Radiative Transfer (DISORT) [Stamnes et al., 1988] is used. DISORT is a model of the transfer of radiation from one location to another by scattering, emission, and absorption in the atmosphere with plane-parallel layers (15 computational layers are used) and a lower bound specified by the surface model described above; the discrete ordinates refer to the discrete polar angles at which the radiative transfer is evaluated. Along with DISORT, a Mars-specific interface is used. This interface, called DISORT multi, was developed by Wolff et al. [2009] and modified, for the purposes of this work, to include a one-term Henyey-Greenstein surface phase function (equation (2)). As with any model, several input parameters are required, and for some of these, the results of previous workers are used. For example, an atmospheric dust particle radius of 1.5 μm (constant with height above the ground) is used, along with a constant vertical dust-mixing ratio and wavelength-dependent dust particle phase function (64 term Legendre expansion) and albedo [Wolff et al., 2009]. The value for dust particle radius mentioned above is quite close to the value obtained by Lemmon et al. [2004]: 1.52 ± 0.18 μm using observations of the atmosphere and surface made using the Panoramic Cameras on the Opportunity rover. Dust is assumed to be present from 0 to 150 km height in the Martian atmosphere. Further inputs to the atmospheric model include surface pressure based on fits to Viking Lander pressure data (differences in elevation are also taken into account assuming an atmosphere in hydrostatic equilibrium) [Tillman et al., 1993] and temperature profiles (with a surface temperature of 260.6 K and atmospheric temperatures ranging from 205.6 K just above the surface to 134.1 K at 55.2 km height at the time FRT0000B6B5 was taken) as well as atmospheric water vapor column abundance (9.1 precipitable micrometers when FRT0000B6B5 was taken) from TES (Thermal Emission Spectrometer, which was on Mars Global Surveyor) climatological data [Smith, 2002] for the appropriate latitude, longitude, and solar longitude Ls (i.e., time of year; see Table 2) from Mars Year 26 (corresponding to April 2002–March 2004) which is taken to be a representative year (spacecraft observations have shown that Martian atmospheric patterns tend to repeat from year to year [Smith, 2008]). The value for the atmospheric optical depth due to dust was taken from Wolff et al. [2009], who derived optical depth for each CRISM Emission Phase Function (EPF) and FRT observation, including FRT0000B6B5 (for this FRT, nadir-looking dust optical depth was 0.43 ± 0.04 at 0.9 μm); this is consistent with the optical depth value obtained via the Panoramic Camera (Pancam) on board the Opportunity rover which gave an estimate of 0.449 ± 0.04 at 0.88 μm on sol 1584 of rover operations, which corresponds to the date FRT0000B6B5 was taken (Planetary Data System Optical Depth Database; see Lemmon et al. [2004] for a description of how optical depth values were obtained). The 0.9 μm optical depth was used to obtain the optical depths at the wavelengths of interest through linear extrapolation, taking
into account the effective aerosol extinction cross section as a function of wavelength for Martian dust [Wolff et al., 2009]. Computations involve 16 streams or discrete polar angles. The consistency of our results (both the self-consistency and the consistency with in situ and near-surface data sets discussed later) indicate that the assumptions mentioned above are reasonable.

3.3. Modeling Atmospheric and Surface Radiance Contributions: Implementation

To derive the best fit surface scattering parameters, modeled CRISM I/F values are compared to the actual CRISM I/F data. To model these data, the surface and atmospheric models are simultaneously implemented in an iterative process that uses the Levenberg-Marquardt least squares approach [Markwardt, 2008]. Input seed values for the surface parameters are fed to the combined surface and atmospheric model. DISORT is used to model the radiative transfer of sunlight as it passes through the Martian atmosphere, then the resulting radiative output is used as input for the surface model (the Hapke model) which is defined within DISORT and gives the amount of light scattered from the surface, this output is then fed back into the atmospheric radiative transfer model within DISORT since the light interacts with the Martian atmosphere again on its way up to the CRISM detector (note that although the surface model is defined within DISORT, it consists of a separate type of radiative transfer model than what DISORT uses for the

Figure 7. Asymmetry parameter map (at 0.801 μm). (a) Full asymmetry parameter map with cooler colors indicating greater small-scale surface roughness. Background is CRISM I/F at 0.801 μm. Artifacts due to topography and other high-χ² pixels are removed. (b) (left) Zoom-in on Victoria crater and ejecta apron and (right) HiRISE image of Victoria with outlined apron.

Figure 8. Corresponding χ² values for parameter maps at 0.801 μm.
atmosphere, as described earlier). The result is the modeled I/F at the CRISM detector, which is compared to the CRISM I/F measurement. The surface scattering parameters $w$ and $b$ are then adjusted, and the procedure is repeated until the best fit to the CRISM data is achieved.

[17] Before using this technique on each individual 11 image deep pixel in a phase cube (as opposed to a spectral cube, a phase cube has phase angle as its third dimension instead of wavelength), a preliminary investigation is conducted in order to find the general region of the parameter space in which the global minimum in $\chi^2$ is located; this preliminary work will allow the determination of appropriate seed values for each parameter to be used for the pixel-by-pixel fits to obtain parameter maps for the study area. This seed parameter determination is accomplished in an efficient manner by taking the whole study area (rather than an individual pixel) as input for the combined surface and atmospheric model. In this manner, average best fit scattering parameter values are obtained for each point on a grid of initial parameter values; this reveals all local minima. Then a grid search is performed to obtain a global minimum in $\chi^2$ space, the corresponding scattering parameter values become the seed parameters for the pixel-by-pixel fits.

[18] After completing the procedure described above, pixel-by-pixel fits are performed, allowing the generation of maps of $w$ and $b$ that can be used to compare the scattering properties of various surface units. To generate these maps, each pixel (corresponding to 11 values of $e$ and $g$ since there are 11 images taken at 11 different viewing angles) is now subjected to the combined surface and atmospheric model described earlier. The seed values obtained as described earlier in this

Figure 9. Data plotted against fit at two selected wavelengths. (top) Data versus fit at 0.801 $\mu$m for $w=0.559$ and $b=-0.187$. The effect of varying $w$ is also shown. (bottom) Data versus fit at 2.271 $\mu$m for $w=0.561$ and $b=-0.250$.

Figure 10. Statistics as a function of wavelength. (top) $\chi^2$ of the model fits as a function of wavelength. (bottom) standard deviation in I/F over the entire study area as a function of wavelength.
section are used to initialize the fitting procedure. The results of the above-outlined procedure are presented along with their interpretation in the following sections.

4. Error Estimation

[19] Using the method described earlier, maps of single-scattering albedo, \( w \) (Figure 6) and asymmetry parameter, \( b \) (Figure 7) were generated for each of the wavelengths studied. These maps cover the area traversed by Opportunity on sols 791–813 and 848–1793. Associated \( \chi^2 \) values for the maps are shown in Figure 8. For pixels where \( \chi^2 \) greatly exceeds the standard deviation (due to the fit being less well constrained for particular pixels), \( w \) and \( b \) values have been flagged as unreliable and are not shown in parameter maps. Certain pixels with above-average \( \chi^2 \) were left in the parameter maps because variations in albedo (observed in the high-resolution central scan or in HiRISE images; often caused by the mixing of exposed bedrock units with soil units in a pixel) contributed to the \( \chi^2 \), so for these pixels, the \( \chi^2 \) value does not indicate a poorly constrained fit; rather, it indicates the extent to which the returned parameters are averages over the different units contained within pixels of different sizes from each image within the FRT. In total, about 3% of the pixels were deemed unreliable. In Figure 9, the top panel shows how I/F at 0.801 \( \mu m \) varies with phase angle for the CRISM data for a pixel with a \( \chi^2 \) value close to average (within 1/5th of a standard deviation). Also plotted is the I/F resulting from the best fit parameters (which were \( w = 0.559 \) and \( b = -0.187 \) for this pixel) for comparison. Since the figure includes actual data that were obtained at varying emergence angles, there are two “arms” to the plot, which is actually a projection from a 3-D space with axes of I/F, emergence angle, and phase angle onto the 2-D space depicted by the figure axes. Included in the figure is a plot with an offset from the best fit \( w \) value for comparison. The bottom panel of Figure 9 shows a similar plot, but for the longest wavelength analyzed in this study: 2.271 \( \mu m \). The fit is worse at this wavelength than at 0.801 \( \mu m \). In fact, the \( \chi^2 \) value of the fit increases monotonically with wavelength, as shown in Figure 10. This is likely related to the general increase in the standard deviation (noise) in I/F with increasing wavelength, also shown in Figure 10. Despite the higher noise at longer wavelengths, results are still constrained enough to identify the average scattering parameter trends with wavelength over the whole study area (as indicated by the observable spectral anticorrelation between single-scattering albedo and asymmetry parameter, and the fact that even at longer wavelengths, \( \chi^2 \) is not high enough to obscure spatial trends; these observations will be discussed further later in the paper). However, for comparison of less spatially extensive regions within the area of interest, it is advisable to rely on the shorter wavelengths, which have the more reliable fits.

[20] In this section, two types of error are discussed: bias and noise (includes physical and instrumental noise). Biases do not affect resulting trends other than by shifting all values by the same amount (in scattering parameter space; i.e., all pixels in an image will be affected in the same manner). Noise (i.e., relative or pixel-to-pixel error) does affect trends.

[21] The principal contributors to bias are uncertainties in atmospheric opacity and atmospheric dust particle radius; these two factors are not independent, but treating them separately gives an outer bound on the bias. The bias is of the same order as the standard deviation in single-scattering albedo and asymmetry parameter over all values covering the study area at a particular wavelength, a quantity which encompasses terrain variations as well as instrument noise; however, changing the optical depth and the atmospheric dust particle radius (note that average values of these quantities are used for the whole scene) did not appreciably change the resulting patterns of variation for either the single-scattering albedo or the asymmetry parameter. This result, taken together with the fact that parameter maps correlate with surface features (as opposed to any less obvious atmospheric features that may be present) indicates

Table 4. The Effects That Various Changes to the Scattering Parameter Calculation Have on Parameter Statistics

<table>
<thead>
<tr>
<th>Reference</th>
<th>Seed w = 0.2</th>
<th>Seed b = 0.3</th>
<th>2 ( \mu m ) Dust Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum w</td>
<td>0.472</td>
<td>0.472</td>
<td>0.485</td>
</tr>
<tr>
<td>Maximum w</td>
<td>0.578</td>
<td>0.596</td>
<td>0.586</td>
</tr>
<tr>
<td>Average w</td>
<td>0.557</td>
<td>0.557</td>
<td>0.568</td>
</tr>
<tr>
<td>Standard deviation w</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Minimum b</td>
<td>-0.260</td>
<td>-0.258</td>
<td>-0.238</td>
</tr>
<tr>
<td>Maximum b</td>
<td>-0.140</td>
<td>0.000</td>
<td>-0.124</td>
</tr>
<tr>
<td>Average b</td>
<td>-0.198</td>
<td>-0.198</td>
<td>-0.179</td>
</tr>
<tr>
<td>Standard deviation b</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Minimum ( \chi^2 )</td>
<td>0.794</td>
<td>0.793</td>
<td>0.280</td>
</tr>
<tr>
<td>Maximum ( \chi^2 )</td>
<td>47.550</td>
<td>47.550</td>
<td>50.636</td>
</tr>
<tr>
<td>Average ( \chi^2 )</td>
<td>3.653</td>
<td>3.721</td>
<td>2.553</td>
</tr>
<tr>
<td>Standard deviation ( \chi^2 )</td>
<td>1.873</td>
<td>2.424</td>
<td>1.878</td>
</tr>
</tbody>
</table>

*The reference computation is 16 stream with a seed value of \( w = 0.5 \) and \( b = -0.2 \). Sensitivity tests shown here were conducted at 0.801 \( \mu m \). Sensitivity tests at 2.277 \( \mu m \) gave similar results.
that the value of the noise is much smaller than that of the biases. 0.801 \( \mu m \) is a useful wavelength for identifying surface features, and this band from the high-resolution central scan of FRT0000B6B5 is shown in Figure 1 and is depicted in large format in Figure 11. In Figure 11, surface features such as craters, wind streaks, strips of bedrock-rich terrain, and an ejecta apron are clearly visible. Given the discussion above, comparing values for different units in FRT0000B6B5 is more accurate than comparing them with units imaged in other FRTs that are taken at different times and therefore different atmospheric conditions (for which one would apply the bias values that will be discussed later in this section), although both types of comparisons will provide useful information. A quantitative procedure for obtaining a noise estimate will also be discussed later in this section.

To obtain an estimate for the magnitude of the biases associated with scattering parameter results, tests of the sensitivity of the results to both the input optical depth and the atmospheric dust particle radius were conducted. Input optical depth values one standard deviation away from the estimated best value were input into the model, and this sensitivity test resulted in a change in the average parameter values over the study area by +0.016, \( -0.017 \) in single-scattering albedo and +0.020, \( -0.023 \) in asymmetry parameter. To test the effect of the atmospheric dust radius being used in the atmospheric correction, this parameter was varied within its error limits and the effect on scattering parameter results was observed. Changing the dust radius from 1.5 to 1.7 \( \mu m \) would test the outer bound on the error limit, but dust-scattering parameters have not been calculated for 1.7 \( \mu m \) radius dust particles, so 2.0 \( \mu m \) was used as the dust radius in this sensitivity test. Table 4 shows the results. Using a larger dust particle radius in the model causes the surface to appear less back-scattering and the single-scattering albedo to appear higher. Using the results at 1.5 \( \mu m \) and at 2.0 \( \mu m \) to linearly interpolate to 1.7 \( \mu m \), we obtain an error estimate of \( \pm 0.0044 \) in single-scattering albedo and \( \pm 0.0076 \) in asymmetry parameter due to the uncertainty in dust particle radius. Additionally, we must take into account any biases in the CRISM I/F values. Following Wolff et al. [2009], we take 5% error as a conservative estimate. The resulting error in single-scattering albedo is \( \pm 0.01 \), and in asymmetry parameter, the resulting error is \( \pm 0.04 \). Summing the contributions from the uncertainty in atmospheric dust particle radius, the uncertainty in atmospheric opacity, and the biases in CRISM I/F values yields a bias in single-scattering albedo of \( \pm 0.03 \) and a bias in asymmetry parameter of \( \pm 0.07 \).

Also of interest is the noise, which affects the reliability of pixel-to-pixel comparisons in the retrieved scattering parameter maps. To obtain estimates for noise, a pixel (which has associated \( w, b, \) and \( \chi^2 \) values) was randomly picked from those that had \( \chi^2 \) values close to the mean (within a fifth of a standard deviation) and the combined inverse modeling described above was run 50 times for that pixel, but random error in I/F was introduced into all but the first run. The standard deviation of the scattering parameters was then taken to be the error in those parameters. In this process, for all except the first run, for each of the 11 input values of I/F, error in I/F was either added or subtracted based on a random Boolean generator. The magnitude of the noise in I/F was determined by taking the standard deviation in I/F of a relatively homogeneous region (Figure 11) of the central scan for each

**Figure 12.** Regions of interest corresponding to spectra in Figure 13. Some near-surface views of terrain near Victoria crater are shown in Figure 27.

**Figure 13.** Scattering parameter spectra for several regions of interest. Near-surface results from Johnson et al. [2006a] for regions with an abundance of spherules are included for comparison (blue line). Error bars, representing noise, are the same for all regions. (left) Single-scattering albedo for the regions of interest shown in Figure 12. Error bars are smaller than the icons representing the regions. Bias is \( \pm 0.02 \). (right) Asymmetry parameter for the regions of interest shown in Figure 12. The error bars are shown on only two regions (southwestern ejecta apron and northwestern bedrock) in order to maintain figure clarity. Bias is \( \pm 0.03 \).
wavelength. Table 3 shows the standard deviations of the scattering parameters at each wavelength. An additional factor that could affect noise is the resolution of the input data; however, higher resolution EPF data would be needed to test this.

Another factor that was investigated in order to determine its contribution to error is the set of seed parameter values used when searching for the best fit between model and data. Table 4 shows how results differ when seed parameter values are changed. It was determined that unless the seed parameter value is at the edge of the parameter space, one can have large differences in seed parameters without much difference in resulting best fit parameter statistics. If the procedure outlined earlier in this section is followed, seed parameters will be robust enough to yield reliable results. Choice of seed parameters does affect the number of outlier pixels.

5. Scattering Property Results at the Opportunity Traverse Region

By concatenating the maps of best fit scattering parameters for several wavelengths (i.e., by creating spectral cubes from these maps), spectra for regions of interest can then be retrieved. Several regions that span the study area (Figure 12) were selected, and Figure 13 shows single-scattering albedo spectra and asymmetry parameter spectra for these regions (see Figure 14 for an average, representative I/F spectrum for the study area. Wavelengths for scattering parameter analysis have been marked on the figure). Note that the names given to regions of interest are general designators, e.g., the region labeled “NW bedrock” does not consist entirely of bedrock, but is more bedrock rich than units labeled “soil”. From the scattering parameter spectra, it is apparent that variations in single-scattering albedo are anticorrelated to variations in the asymmetry of the phase function, in the spectral domain (see also Figures 15 and 16). The entire study area is backscattering at all wavelengths studied; however, some regions are more backscattering than others. The region (shaded red for visualization in Figure 12) located in the southwestern portion of Victoria’s ejecta apron is relatively free of aeolian deposits and is more backscattering than other regions of interest (including regions of the ejecta apron where wind streaks are located; see Figure 15).

Figure 14. Plot of average (100 × 101 pixel; approximately 1790 m × 1790 m) spectrum of region inclusive of Victoria crater and its ejecta apron. Spectrum taken from original TRR3 I/F data for FRT0000B6B5. Vertical lines indicate wavelengths used in the analyses presented in this paper.

Figure 15. A comparison of the backscatter from two regions on Victoria’s ejecta apron. The cyan region represents the basaltic wind streaks coming from the northeastern rim of Victoria. The red region represents an area in the southwestern portion of Victoria’s apron that, from morphology, is relatively free of aeolian deposits compared to other sections of the ejecta apron. Error bars shown in the figure represent noise or pixel-to-pixel error. Bias which will not change the trend but will shift it up or down (to higher or lower asymmetry parameter) is ±0.03 and depends on atmospheric parameter estimates.
Additionally, there is a general trend in which surfaces become more backscattering with increasing wavelength (the increase in noise in I/F with wavelength mentioned in section 4 might be contributing to this trend, but if it were the dominant effect, one would expect more erratic spectral behavior). Figure 17 shows a plot of asymmetry parameter versus single-scattering albedo at 0.801 μm for the entire study area. From this plot, it is apparent that, with regard to spatial variation, the asymmetry parameter increases as single-scattering albedo increases. Similar plots at other wavelengths show the same trends. However, as discussed earlier in this section, if instead of looking at the spatial variations at any given wavelength, the variations in the spectral domain are considered, the opposite trend is observed (compare Figure 15 with Figure 16 to see the inverse relationship). Essentially, spatial variations in single-scattering albedo have a direct positive correlation with spatial variations in the asymmetry of the phase function, whereas in the spectral domain, variations in single-scattering albedo are anticorrelated to variations in the asymmetry of the phase function. This observation does not represent an inconsistency; rather, it suggests that the surface property which has a dominant effect on the relationship between spatial variations in w and b is not the same as the surface property which has a dominant effect on the relationship between variations in w and b in the spectral domain.

To inspect the variations along the trend line in the b versus w plot, different areas along the trend line were colorized and then mapped to where they occur on the surface. This is shown in Figure 18. The top panel shows that the class of region designated by cyan and pink colors has high single-scattering albedo and high-asymmetry parameter values. The bottom panel of the figure indicates that this class corresponds to a relatively bedrock-rich curved strip of terrain. Classes designated yellow and dark blue are in the middle of the w-b trend line, and they are located on either side of the bedrock-rich strip of terrain. And even further to either side are the green and red classes, which have low single-scattering albedos and low-asymmetry parameters. The pink and red classes can be taken as endmembers. Figure 19 shows HiRISE images corresponding to six pixels in the

![Figure 16. Plots of single-scattering albedo versus wavelength for the same regions as shown in Figure 15. Note the anticorrelation between the plots shown here and the plots in Figure 15.](image1)

![Figure 17. Spatial trends in b versus w (for the 0.801 μm band). (top) plot of b versus w for the entire study area. (bottom) same as the top panel except the data points from Victoria’s ejecta apron are colored magenta. (right) Zoom-in on density plot, warmer colors indicate a higher density of (w, b) points. Values listed in red are correlation coefficients. The cluster to the right corresponds largely to the region to the west of Victoria crater, and the cluster on the left corresponds largely to the region to the east of Victoria crater.](image2)
Figure 18. A closer look at the $b$ versus $w$ trend line. The top panel shows a plot of $b$ versus $w$ at 0.801 μm for entire study area, with different sections along the positive trend line designated by color and mapped to location in the bottom panel. Note that the regions designated by pink and red represent bedrock-rich and bedrock-poor endmembers, respectively (see Figures 19 and 20).

Figure 19. HiRISE image subsections that each cover the same area as a pixel from the high-albedo, high-asymmetry parameter class designated in pink in Figure 18. Subsections taken from HiRISE image PSP_009141_1780_RED.

Figure 20. HiRISE image subsections that each cover the same area as a pixel from the low-albedo, low-asymmetry parameter class designated in red in Figure 18. Subsections taken from HiRISE image PSP_009141_1780_RED.

High-albedo, high-asymmetry parameter pink class, and Figure 20 shows HiRISE images corresponding to six pixels in the low-albedo, low-asymmetry parameter red class. It is apparent from these HiRISE images that the pink endmember has a greater bedrock component than the red endmember. For classes that are adjacent to each other in $w$-$b$ space, the difference is not distinguishable by eye, as it is for the endmembers. There are also some regions that are located away from the main trend line. Notably, several wind streaks emanating from Victoria crater are lower albedo and less backscattering than most other soils (Figure 21).

6. Comparison of Orbital and Rover Scattering Parameter Results

[27] Meridians Planum is one of seven regions on Mars where there exist both orbital and near-surface observations at time of publication. This combination of data sources is beneficial for the interpretation and validation of scattering parameter results. While this section focuses on the comparison of the scattering parameters themselves, the next section will treat near-surface images and how they aid in interpretation of the orbital results. Included in Figure 13 is a comparison with the results of Johnson et al.’s [2006a] spectroscopic analyses based on data acquired from the ground by the Opportunity rover. The blue curves represent results from near-surface observations of an endmember soil type that is covered densely with hematite-rich, spherical concretions. For completeness, Figure 22 includes the Hapke roughness parameter [Hapke, 1993; Johnson et al., 2006a, 2006b] from Johnson et al.’s [2006b] analysis of Opportunity’s observations of this soil type, alongside the CRISM-derived asymmetry parameter. However, in the case of the roughness parameter, an average value was not plotted, because only one region (labeled Plains near Alvin Crater) had a roughness parameter constrained at more than one wavelength. Note that the trends exhibited in the spectral variation of the scattering parameters are similar for both the orbital and the ground-based analyses. It is not surprising that the single-scattering albedo obtained from the orbital observations is higher than that obtained from ground and the asymmetry parameter is lower. This result is partially due to the fact that, in images acquired from orbit, each pixel consists of multiple surface units (often including bright bedrock), not just a spherule-covered soil endmember. Further, Johnson et al. [2006a] used a version of the Hapke model that had a separate parameter for roughness [Hapke, 1993], so their asymmetry parameter should not be affected as much by roughness. Since roughness causes more backscatter, the asymmetry parameter values in the current study are more negative than those of Johnson et al. [2006a].
Therefore, differences in results are consistent with what is expected due to differences in models, but results still show marked similarities.

7. Surface Roughness at the Opportunity Traverse Region: Large-Scale Roughness

Now that surface scattering parameters have been mapped for the extent of the study area, the next step is to determine which surface characteristics are responsible for the observed scattering patterns. There is meter-scale roughness in this region, in the form of north-south trending ripples. It is reasonable to compare scattering patterns seen in Figures 6 and 7 to ripple wavelength (crest-to-crest distance, which is directly related to ripple height) which varies in this region. Figure 3 shows a map of ripple wavelength, with warmer colors indicating larger ripples. There does not appear to be a strong correlation between ripple wavelength and scattering behavior (correlation coefficient of 0.10). For example, in terms of ripple wavelength, Victoria’s ejecta...
apron looks relatively homogeneous, whereas, parts of the ejecta apron are more backscattering than other parts. Additionally, there are many large ripples just outside Victoria’s apron, but this variation in ripple cover does not appear to translate to a difference in scattering properties. This result is probably at least partially due to the observational setup and its relation to ripple orientation. Ripples in this region trend north-south and CRISM’s flight path is south to north, so all the phase information is in that direction. However, one might expect some slight effect due to the fact that the ripples merge and fork, creating regions where one would expect shadowing in the north-south direction. Ripple characteristics can be seen in the close-in views of ripples shown in Figures 19 and 20.

8. Surface Roughness at the Opportunity Traverse Region: Small-Scale Roughness

[29] Since large-scale roughness does not appear to have a strong influence on scattering properties, there must be a different surface property that can explain the observed scattering patterns. Small-scale (millimeter-scale) roughness on and around the Opportunity traverse is dominated by the presence of hematite-rich, spherical concretions and is also affected by differences in bedrock and soil texture. The size and burial depth of the spherules (both of which affect areal abundance) significantly affects the scattering characteristics observed from orbit, as will be shown later in this paper. The hematite-rich spherules responsible for the millimeter-scale surface roughness at the Opportunity traverse region have been studied by several workers, and summaries are given by Calvin et al. [2008] and Weitz et al. [2006]. Therefore, just a few spherule characteristics will be mentioned here. Spherules are 2–5 mm in size in the area around Victoria crater [Geissler et al., 2008], and on average, 2.9 ± 1.2 mm over much of the traverse leading to Victoria crater [Weitz et al., 2006]. Hynek and Singer [2007] found that the size of the hematitic spherules observed by Opportunity appears to be directly correlated with thermal inertia, independent of spherule abundance. Given the variations in spherule size at Victoria’s apron, one might expect this variation to translate to variations in thermal inertia (Figure 23); however, the situation is more complicated because bedrock is also a factor, and the transition to the apron is also a transition to very low bedrock exposure; further, spherule burial is a factor.

[30] Figure 11 shows the CRISM I/F at 0.801 μm, a wavelength at which surface features are easily identified. Some features are labeled, several of which incorporate wind-blown material. It is possible, from looking at these features, to make inferences regarding small-scale surface roughness. Aeolian deposition often has a smoothing effect at millimeter scales, and wind streaks, as well as craters filled with aeolian deposits, tend to be relatively smooth at these scales compared with other regions in the study area (see Figure 24 for rover observations showing textural smoothing). This smoothness is interpreted to be due to sand and dust, which have been blown into gaps between spherules, thus burying the spherules and smoothing the surface out. In Figure 6, wind streaks extending from the eastern rim of Victoria are fainter than wind streaks extending from the northeastern rim (this is likely due to}

Figure 23. Zoom-in on thermal inertia of Victoria’s apron and surroundings.

Figure 24. Images of hematite-rich spherules taken with the Opportunity rover’s Microscopic Imager. In the left panel, spherules have been buried, resulting in a texturally smoothed surface, whereas in the right panel, spherules have not been buried as deeply by aeolian material. Note that Geissler et al. [2008] looked at the photometry of the same regions in situ and obtained comparable results to those presented here.
variable basaltic sand cover). In Figure 7, it is apparent that even the fainter wind streaks have a higher asymmetry parameter than the rest of the ejecta blanket.

[31] In the region surrounding Opportunity’s traverse, hematite-rich spherules are embedded in bedrock, and they are harder than the bedrock, so when the bedrock weathers away, they are preserved as a lag deposit. Therefore, the more weathered, soil-rich surfaces will have denser spherule cover and greater small-scale roughness than more bedrock-rich surfaces. Additionally, spherule size decreased as Opportunity drove upslope (and likely upsection) toward Victoria crater; however, spherule size increased again once Opportunity reached Victoria crater’s ejecta apron, likely because the ejecta blocks came from depth (layers similar to those seen earlier in the traverse) [Squyres et al., 2009]. The spherule size difference related to Victoria’s ejecta apron can be seen in Figure 25. Looking back at Figure 7, Victoria’s ejecta apron (excluding sections located on large wind streaks) is more backscattering than surrounding regions, this indicates a correlation between spherule size and amount of backscatter, likely due to the effect of spherule size on the amount of spherule exposed. Interestingly, the fact that the backscattering pattern is dominated by spherule-related roughness rather than ripple-related roughness is in agreement with the work of Shepard and Campbell [1998], although that study was conducted on fractal surfaces. After investigating several model surfaces, Shepard and Campbell [1998] note the following: “We hypothesize that the scale which dominates surface shadowing and by extension photometric roughness is the smallest surface scale for which shadows exist.” Further, other workers, including Goguen et al. [2010] who investigated lunar photometry, have noted that submillimeter- and millimeter-scale roughness have the greatest effect on observed photometry as compared to larger-scale roughness. The reason small-scale roughness dominates the photometric signature from roughness is likely because, for natural surfaces, slopes are often highest at small spatial scales. It is at the smaller scales that one is more likely to find higher cohesion values that take the slopes to angles greater than the angle of repose [Helfenstein, 1988].

[32] In light of the information presented in this section on the relation between asymmetry parameter and millimeter-scale roughness, it is instructive to revisit Figure 17. Since a more negative asymmetry parameter indicates a rougher surface at small scales, Figure 17 indicates that as single-scattering albedo goes up, apparent small-scale roughness decreases. As a consistency check, it is worthwhile to see if the trend between asymmetry parameter and single-scattering albedo corresponds to the trend between roughness and single-scattering albedo observed by other workers. Johnson et al. [2006a, 2006b] see the same trend between roughness (in their case, roughness is in the form of the Hapke roughness function).
parameter $\Theta$ bar) and single-scattering albedo in their results based on near-surface Panoramic Camera (Pancam) observations at both Meridiani Planum [Johnson et al., 2006a, Figure 6] and Gusev crater [Johnson et al., 2006b, Figure 10]. For the study area shown in Figure 6, the observed $b$ versus $w$ trend in Figure 17 is in large part due to surface roughness caused by hematite-rich spherules. As shown in Figure 18, the trend line is a mixing line between bedrock-rich and bedrock-poor endmembers. High-albedo surfaces are in general more bedrock rich, and bedrock in this area tends to be less rough than soil on millimeter scales (see Figure 26); this is due to fewer hematite-rich spherules on the surface of bedrock than on the surface of soil. These spherules will be discussed in more detail later in this paper.

[33] As has been shown, for several regions in the study area, small-scale surface roughness can be observed from the ground. These regions include relatively bedrock-rich areas as well as areas with large ripples, and notably, Opportunity has traversed Victoria’s ejecta apron including wind streaks extending away from Victoria’s rim. Most of Victoria’s apron is very well eroded and exhibits a dense cover of relatively large hematite-rich spherules (Figures 25 and 27). This textural cover results in a more backscattering surface than surrounding regions, as can be seen in the

Figure 27. View from the ground: these images taken by the Opportunity rover show Victoria’s ejecta apron and the bedrock just beyond. Note the small ripples and dense spherule cover on the ejecta apron.

Figure 28. Asymmetry parameter maps as a function of wavelength. Note that the map at 0.566 $\mu$m has the lowest associated error. For scale, Victoria crater, in the approximate center of each image, is ~750 m wide. The same color scale is used for the three shortest wavelengths, but this convention was not followed at longer wavelengths in order to display the full spatial variability of the asymmetry parameter.
CRISM-scattering parameter results (Figures 7 and 15). Figure 28 shows that the same overall patterns occur in maps of asymmetry parameter made at several different wavelengths, which is to be expected from patterns dominated by a shadowing effect due to surface roughness. There are regions of the ejecta apron that are less backscattering, namely, several wind streaks on the northern and eastern portions of the apron. This correlation indicates that small-scale roughness is dominating the amount of backscatter seen from orbit. Further, there is confirmation of this effect from in situ and near-surface observations, specifically rover-acquired data analyzed by Geissler et al. [2008]. Figure 24 shows images from the rover’s Microscopic Imager (MI) taken both off-wind-streak and on-wind-streak. It is apparent that the burial depth of the spherules is greater for areas in wind streaks as material has been deposited between spherules. Geissler et al. [2008] conducted a photometric analysis of these regions using rover Pancam images at 0.754 μm and showed that areas on the wind streak are less backscattering. Essentially, what is happening is the spherules are topographic elements that create a shadowing effect resulting in the preferential backscatter (note the 56–57° incidence angles in the observation; Table 1). Table 5 summarizes the relationship between backscatter and spherules. This relationship has also been observed in lab experiments conducted by Johnson et al. [2007] in which hematite-rich spherules were removed from an analog sample paleosol from Sioux City, Iowa, and its scattering properties were determined from matrix powder, then the spherules were reintroduced, and a significant increase in backscatter was observed as well as a significant decrease in albedo. Additionally, McGuire and Hapke [1995] looked at individual opaque spheres with rough surfaces and found them to be backscattering.

Earlier, it was mentioned that the surfaces in the region Opportunity has been traversing tend to become more backscattering with increasing wavelength. The simplest explanation for this trend would be that the topographic elements (spherules) that are causing the shadowing effect (and therefore the backscatter) have different spectral properties than the rest of the surface. In order to be consistent with the observed spectral trend in backscatter, the ratio of spherule brightness to substrate brightness must increase at long wavelengths (longer than 1.009 μm). Unfortunately, spherule and substrate spectra at these long wavelengths have not been acquired (the longest wavelength Pancam detects is 1.009 μm). As a qualitative example of the spectral differences that would be in accord with the observed backscatter trend, Figure 29 shows spectra of hematite and basalt from the CRISM Spectral Library (available online through the Planetary Data System’s Orbital Data Explorer). If the spherules are brighter than the substrate at longer wavelengths, the backscattered light should be redder than the forward-scattered light. These differences should lead to a pattern where backscattering increases with increasing wavelength (since the spherules would get more reflective with increasing wavelength), as is seen in Figure 13. To further investigate the implications of the derived wavelength-dependent single-scattering albedo and asymmetry parameter, these parameters were used to reconstruct I/F at various illustrative viewing geometries, all corresponding to an incidence angle of 30°, but with varying emergence and phase angles. Figure 30 shows the results: the most backscattering parameters tend to increase with increasing wavelength.
Figure 30. Reconstructed I/F values at various observation geometries, for the best fit scattering parameters.

geometry corresponds to the reddest spectrum. This agrees with the asymmetry parameter being the most negative at the reddest wavelength (2.27 μm) investigated. This would make sense in terms of the spectral properties of spherules only if they are redder than basalt (i.e., redder slope over the whole wavelength range being considered).

[35] To draw an analogy with the idealized situation, for a surface consisting of a substrate with spherules strewn on top, if that surface is viewed in a nadir-looking geometry, then the ratio of underlying substrate to overlying spherules in the resulting image is maximized. However, for the other endmember in terms of viewing geometry, which consists of viewing the surface from the horizon (i.e., an edge-on view), only the spherules that protrude above the substrate will be seen. Therefore, if the substrate and the spherules have differing spectral characteristics, then nadir-viewing geometry will have more of a contribution from the spectrum of the underlying plane and as the emergence angle becomes more oblique, the resulting average spectrum of the scene will have more of a contribution from the spectrum of the spherules.

[36] This situation is not unique to Meridiani Planum, as rocks tend to be made of materials with both different physical properties (in particular, hardness) and different spectral properties. Softer materials will erode to finer particle sizes, and be sifted down below the larger particles/pebbles/cobbles to form the underlying substrate. Thus, spectra taken at larger emergence angles will have more of an influence from the spectral signature of the larger particles/pebbles/cobbles than spectra taken at nadir geometry.

[37] In summary, thus far, the atmospheric and surface contributions to observed reflection have been separated in order to map scattering parameters for the entire study area. Data from the portion of the study area traversed by the Opportunity rover have been used to confirm that the dominant factor affecting the backscatter pattern is millimeter-scale roughness. Note that no assumptions have been made about how roughness is parameterized, instead, after deriving the phase function and upon comparison to near-surface observations, it was determined that the dominant effect on the anisotropy of the phase function is millimeter-scale roughness, which in this region is primarily due to the presence, size, and burial depth of hematite-rich spherules. Further, the available information on surface roughness has been extended to a much larger region that stretches for kilometers to the east and west of the rover traverse.

9. Conclusion

[38] At the Opportunity traverse area, the information on and interpretations of surface scattering have been spectrally and spatially extended relative to previous studies by generating maps of single-scattering albedo and asymmetry parameter at visible and near-infrared wavelengths. Backscattering of incident light is observed to increase with wavelength longward of 1 μm. Additionally, backscatter increases as the abundance of larger (3–5 mm) spherules increases because their presence results in a corresponding increase in roughness at the 3–5 mm scale. The abundance of large spherules increases over Victoria crater’s ejecta blanket, and this can be seen from the amount of backscatter observed from orbit. Changes in spherule size are indicative of changes in composition or amount of water present during spherule formation [Squyres et al., 2006a, 2006b]. Observable differences in backscatter also include a backscatter decrease that results from the burial of spherules in sand and dust at the wind streaks emanating from Victoria crater. Bedrock-rich and bedrock-poor regions also differ in observed backscatter; bedrock-rich regions are less backscattering and have fewer exposed spherules than bedrock-poor regions.

[39] The single-scattering albedo of the surface varies from 0.42 to 0.57 (0.5663–2.2715 μm) for the study area. The asymmetry parameter of the surface varies from −0.27 to −0.17 (0.5663–2.2715 μm) for the study area. Negative values for asymmetry parameter indicate a backscattering surface. In the spectral domain, backscatter increases with increasing albedo. In the spatial domain, backscatter decreases with increasing albedo.

[40] The orbital and near-surface analyses presented in this work are in agreement with each other as well as with previous near-surface analyses and laboratory measurements. In this work, a procedure has been outlined for combined modeling of atmospheric and surface contributions to scattered light. Use of these methods will also be advantageous for future analyses of regions visited by spacecraft as well as those that have not been observed in situ.

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