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Characterizing the thermal infrared spectral effects of optically thin surface dust: Implications for remote-sensing and *in situ* measurements of the martian surface

Frances Rivera-Hernandez [a,*], Joshua L. Bandfield [b], Steven W. Ruff [c], Michael J. Wolff [b]

[a] *Department of Earth and Planetary Sciences, University of California-Davis, 1 Shields Avenue, Davis, CA 95616, USA*
[b] *Space Science Institute, 4750 Walnut St., Ste. 205, Boulder, CO 80301, USA*
[c] *School of Earth and Space Exploration, Box 6305, Arizona State University, Tempe, AZ 85287, USA*

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ABSTRACT

A spectral contribution different from that observed for thick dust mantles has been identified in many of the *in situ* measurements of rocks and regolith acquired by the Miniature Thermal Emission Spectrometer (Mini-TES) instruments on the Mars Exploration Rovers (MER). This spectral contribution is thought to be caused by optically thin surface dust and if not corrected can greatly hinder the mineralogical interpretation of rock surfaces. The focus of this study is the characterization of key radiative processes that are necessary to understand the spectral contributions produced by optically thin surface dust. An understanding of these radiative processes is important to be able to reproduce, predict, and correct their contribution in thermal infrared (TIR; ~200–2000 cm^{-1}; 5–50 μm) datasets. By combining TIR spectroscopic laboratory measurements and radiative transfer (RT) modeling, we have reproduced and quantified the spectral contributions produced by optically thin surface dust in the TIR spectral range. TIR laboratory measurements were acquired of basaltic rocks and gold diffuse reflectors (GDR) mantled with varying amounts of optically thin dust. The spectral contributions of optically thin dust as observed by Mini-TES were not observed in the laboratory measurements of the dusty basaltic rocks, but were observed in the measurements of the dusty GDR's. For the dust to contribute spectral features the dust must maintain a thermal contrast with the underlying surface. This thermal contrast was not achieved for the dusty basaltic rocks. Using our RT model, laboratory spectra of the dusty basaltic rocks and GDR's were reproduced. Our RT model appears to reproduce the spectral features attributed to the dust in the laboratory measurements to first order and can quantify the relationship between dust coatings and measured radiance. After validating the RT model against the TIR laboratory measurements, it was then used in an initial application to reproduce measurements acquired by the Mini-TES. By characterizing the spectral behavior of the dust, including the potential for thermal contrast between the dust and the substrate, it is possible to better understand and interpret TIR spectra of dust mantled surfaces.

1. Background and motivation

1.1. Effects of dust in thermal infrared spectroscopic measurements

Dust is one of the most common complicating factors in the acquisition and interpretation of spectral datasets from the martian surface. Observations acquired at the Mars Science Laboratory (MSL), MER, Viking, Phoenix, and Pathfinder landing sites have all shown dust coated surfaces and changes attributed to aeolian dust deposition (*e.g.*, Ruff et al., 2006; Smith et al., 2006; Moore and Jakosky, 1989). Even with the use of a tool to remove surface dust deposits (*e.g.*, brush), as is done by the MSL and MER rovers, surfaces are not entirely clean and the interfering effects of dust are still present, if also subdued. Dust is a component in spectral remote sensing datasets of Mars that cannot be avoided.

The spectral effects attributable to dust in TIR datasets are temperature and wavelength dependent and can be highly variable. For example, the spectral effects can vary depending on the composition of the dust, where the dust is located in the field of view (*e.g.*, instrument mirror, rock surface, atmosphere), the amount of dust present, and on the physical properties of the dust (*e.g.*, particle size). Neglecting the possible effects caused by dust can lead to the obscuration or misinterpretation of important compositional properties that are necessary to determine current and past

* Corresponding author.

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processes on planetary surfaces. Methods to remove the spectral signature of dust in TIR measurements have allowed for successful interpretation of TIR datasets of the martian surface (*e.g.*, Bandfield and Smith, 2003; Ruff and Christensen, 2002). However, recently recognized spectral effects attributed to optically thin dust coatings have not been previously addressed and are the focus of this paper.

If dust is in the field of view of a detector, it will contribute emitted radiance to the scene. Whether the scene radiance is dominated by radiative contributions from dust emission, versus that due to absorption and/or scattering, is primarily dependent on the optical thickness and temperature of the dust. Optical thickness, $\tau(\lambda)$, is a unitless parameter that is used to quantify the amount of surface radiance that is attenuated (absorption and/or scattering) by a dust layer over a discrete distance, *ds*. The value *ds* is the physical length that the radiance must travel through from the emitting surface to the detector. For simplicity, the terms optically thin and optically thick are used in the rest of our discussion. Optical thickness is proportional to the abundance of particles that are present in the direction of propagation of the emitted radiance and is also determined by the wavelength-dependent absorptive properties of any given composition.

In general, for optically thick dust particles with many potential radiative interactions, the bulk of the radiance from the underlying surface will be absorbed or scattered. In this case, radiance emitted by the dust itself will dominate the measurement. Optically thin dust particles on the other hand, absorb and scatter radiance from the underlying surface to a much lesser degree. In this case, whether the scene has non-negligible radiative contributions from the dust is dependent on the temperature of the dust. If the dust has the same temperature as the surface, the dust will contribute as much radiance as it absorbs, with no net effect except minor scattering contributions. The magnitude of the contribution from the dust is dependent on the temperature of the dust relative to the substrate. If the dust has a thermal contrast with the underlying surface, these spectral features will be evident in TIR datasets.

Optically thin and thick dust have fundamentally different radiative contributions, and produce different spectral features in TIR measurements (Fig. 1). The spectral behavior of thick dust mantles have been extensively studied (*e.g.*, Korb et al., 1999; Salisbury and Wald, 1992; Logan and Hunt, 1970; Conel, 1969). These studies have concluded that there is generally a decrease in the spectral contrast of primary absorption features in the measured emissivity of particulate samples compared to their solid form. This is mostly due to absorption and internal multiple scattering of radiance between the particulates. The decrease in contrast of reststrahlen bands is accompanied by the appearance of transparency features (*e.g.*, Ruff and Christensen, 2002). Although thick dust mantles also play an important role in remote sensing of planetary surfaces, including Mars, our focus here are the spectral effects and underlying radiative processes associated with optically thin dust coatings.

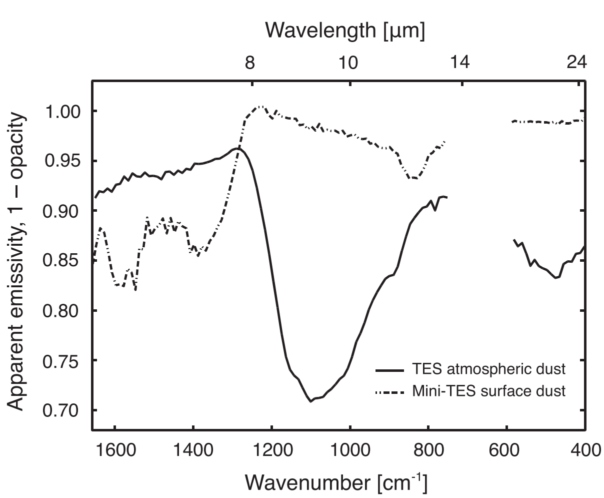

Fig. 1. TES spectral shape of atmospheric dust (1 – opacity; Bandfield and Smith, 2003) and a Mini-TES surface dust spectrum (apparent emissivity) to highlight spectral differences between optically thin and thick dust. The atmospheric dust spectrum is representative of the spectral character of optically thin dust, whereas the undisturbed soil measurement taken by Mini-TES is representative of the spectral character of optically thick dust. The Mini-TES spectrum is data product p3654 from sol 078.

1.2. Previous investigations and identification of the effects of dust on rock surfaces in TIR spectroscopic measurements

Previous investigations have attempted to characterize and understand the TIR spectroscopic effects of dust mantles (dust coatings) (*e.g.*, Graff, 2003; Johnson et al., 2002; Crisp and Bartholomew, 1992). These investigations compared measurements of clean (dust free) rock surfaces to those of surfaces deposited with variable amounts of dust. These investigations show a decrease in the spectral contributions from the substrate with increasing amounts of dust. If sufficiently thick, the dust completely obscured the radiance emitted from the underlying surface, and the radiance contribution from the dust dominated the scene (*e.g.*, Graff, 2003; Johnson et al., 2002). The spectral contributions of the dust observed in these measurements are characteristic of optically thick dust that obscures the substrate in a checkerboard fashion. In a checkerboard model, the dust and rock are assumed to emit radiance independently so that,

$$R_m = \alpha R_{rock} + (1 - \alpha) R_{dust}, \tag{1}$$

where R_m is the measured radiance, R_{rock} is the radiance emitted by the rock, R_{dust} is the radiance emitted by the dust, and α is the fraction of the radiance emitted from the rock in the measurement.

The spectral contributions observed in the laboratory for optically thick dust are also observed in spacecraft and *in situ* TIR datasets of the martian surface. These are characteristic of moderate and high albedo martian surfaces (*e.g.*, Bandfield and Smith, 2003; Ruff and Christensen, 2002). Although the spectral features attributed to optically thick surface dust make remote compositional characterization more difficult, they are also relatively well understood and straight forward to identify and model in TIR datasets (Ruff et al., 2006; Bandfield et al., 2000). This assumption allows a dust contribution to be calculated and removed from the original data using a linear least-squares fitting routine with a resulting spectrum that only contains the spectral signature from dust-free surfaces. This procedure has successfully provided corrected spectra of the martian surface using Mars Global Surveyor Thermal Emission Spectrometer (MGS TES) and 2001 Mars Odyssey Thermal Imaging System (THEMIS) data (*e.g.*, Bandfield et al., 2004, 2000).

1.3. Spectral contributions produced by optically thin surface dust in Mini-TES measurements

A spectral contribution different from that documented for surface dust in previous laboratory and spacecraft TIR measurements has been identified in many of the *in situ* measurements of rock and regolith acquired by the Mini-TES instruments on the MER (Fig. 2; Hamilton and Ruff, 2012; Ruff and Bandfield, 2010). This spectral contribution is thought to be caused by thin mantles of dust (<~10 µm thick) and is referred to as the optically thin surface dust component by Hamilton and Ruff (2012). The dust is