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Determining mineralogical variations of aeolian deposits using thermal infrared emissivity and linear deconvolution methods

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ABSTRACT

We apply linear deconvolution methods to derive mineral and glass proportions for eight field sample training sites at seven dune fields: (1) Algodones, California; (2) Big Dune, Nevada; (3) Bruneau, Idaho; (4) Great Kobuk Sand Dunes, Alaska; (5) Great Sand Dunes National Park and Preserve, Colorado; (6) Sunset Crater, Arizona; and (7) White Sands National Monument, New Mexico. These dune fields were chosen because they represent a wide range of mineral grain mixtures and allow us to gauge a better understanding of both compositional and sorting effects within terrestrial and extraterrestrial dune systems. We also use actual ASTER TIR emissivity imagery to map the spatial distribution of these minerals throughout the seven dune fields and evaluate the effects of degraded spectral resolution on the accuracy of mineral abundances retrieved. Our results show that hyperspectral data convolutions of our laboratory emissivity spectra outperformed multispectral data convolutions of the same data with respect to the mineral, glass and lithic abundances derived. Both the number and wavelength position of spectral bands greatly impacts the accuracy of linear deconvolution retrieval of feldspar proportions (e.g. K-feldspar vs. plagioclase) especially, as well as the detection of certain mafic and carbonate minerals. In particular, ASTER mapping results show that several of the dune sites display patterns such that less dense minerals typically have higher abundances near the center of the active and most evolved dunes in the field, while more dense minerals and glasses appear to be more abundant along the margins of the active dune fields.

1. Introduction

The future launch of the spaceborne Hyperspectral Infrared Imager (HyspIRI), together with the deployment of ECOSTRESS on the international space station (ISS), will mark a milestone toward the goal of achieving complete hyperspectral coverage of the Earth with thermal infrared (TIR) emissivity data that are comparable to or of better resolution than TIR sensors formerly and currently in operation around Mars. These data, together with an archive of existing Advanced Spaceborne Thermal Emission and Reflection (ASTER) imagery collected since 1999 will provide an opportunity to map the abundance and distribution of minerals in aeolian deposits that will provide insight into provenance, transport and sorting processes that occur in active dunes. Analytical methods widely used to process and interpret TIR emissivity imagery of Mars can also be applied to equivalent or better imagery of Earth. In contrast to Mars, terrestrial aeolian sediments can be directly sampled to provide ground truth and laboratory data to correlate with the imagery without the need of landing rovers or astronauts.

Thermal infrared (TIR) emissivity data provide an important means to address a variety of geologic problems associated with aeolian deposits, including lithologic properties, transport pathways, dust emission sources and provenance (Ramsey et al., 1999; Bandfield et al., 2002; Michalski et al., 2004; Katra and Lancaster, 2008; Katra et al., 2009; Scheidt et al., 2010). In contrast, satellite visible to short-wave infrared (VSWIR) reflectance data have been used more widely in terrestrial aeolian studies because datasets covering this wavelength range are more readily available for the Earth (e.g., Jacobberger, 1989; Jacobberger and Hooper, 1991; Blount et al., 1990; Paisley et al., 1991; Okin and Painter, 2004; Ballantine et al., 2005; Ghrefat et al., 2007 and references therein; Hooper and Necsoiu, 2014). Unfortunately, many of the latter studies were only able to distinguish active versus inactive sands based on vegetation cover, soil formation, and brightness/albedo differences related to grain size variations and perhaps moisture contents of (predominantly quartz and feldspar) minerals, which have characteristically flat and featureless spectra at VSWIR wavelengths. Ironically, more extensive and higher spectral resolution TIR emissivity coverage of Mars exists at regional to global scales [e.g., Thermal

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Table 1
Summary and comparison of highest resolution terrestrial and Martian TIR emissivity sensors.

TIR sensor	Planet	Airborne or spaceborne	Spatial resolution	Spectral resolution	References
ASTER (Advanced Spaceborne Thermal Emission and Reflection)	Earth	Spaceborne	90 m[*]	5 ms	Yamaguchi et al. (1998)
ECOSTRESS (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station)	Earth	Spaceborne	~70 m[**]	5 ms	Hulley and Hook (in press)
TIMS (Thermal Infrared Multispectral Scanner)	Earth	Airborne	Variable	6 ms	Palluconi and Meeks (1985)
HyspIRI (Hyperspectral Infrared Imager)	Earth	Spaceborne	60 m	7 ms	Abrams and Hook (2013)
MASTER (MODIS-ASTER Airborne Simulator)	Earth	Airborne	Variable	10 ms	Hook et al. (2001)
Sebass (Spatially Enhanced Broadband Array Spectrograph System)	Earth	Airborne	Variable	128 hyp	Kirkland et al. (2002)
MAKO (MAKO Long Wave Infrared Imaging Spectrometer)	Earth	Airborne	Variable	128 hyp	Warren et al. (2010)
HyTES (Hyperspectral Thermal Emission Spectrometer)	Earth	Airborne	Variable	256 hyp	Hook et al. (2013)
THEMIS (Thermal Emission Imaging System)	Mars	Spaceborne	100 m	10 ms[***]	Christensen et al. (2004)
TES (Thermal Emission Spectrometer)	Mars	Spaceborne	3 km[**]	143 hyp[***] 286 hyp[***]	Christensen et al. (2001a)

Note. Sensors are listed in order of increasing number of bands in the 8–14 μm range. Those sensors with greater than 50 bands are multispectral (ms) and those with greater than 50 bands are hyperspectral (hyp). Spectral resolution characteristics and hyperspectral to multispectral data convolutions used prior to spectral unmixing are discussed in Section 3.3. Spatial resolutions of the airborne sensors are variable, and depend in part on flight altitude (see Section 3.4).

[*] Derivative Global Emissivity Datasets such as the North American ASTER Land Surface Emissivity Database (NAALSED) are resampled to 100-m resolution, continental-scale gridded datasets (e.g., Hulley and Hook, 2009).

[**] Will vary between 38.5 m and 68.5 m per pixel, depending on orbital height. ISS nominal altitude range is from 385 to 415 km (Hulley and Hook, in press).

[***] Note that the Martian atmospheric window of remote sensing is different from that of the Earth, such that Mars has minimal H_2O vapor- and O^3 gas-related absorption bands that effectively lower atmospheric transmission through Earth's atmosphere at TIR wavelengths outside of the two 3–5 and 8–14 μm atmospheric windows. Therefore, Martian hyperspectral emissivity measurements can effectively be collected between 6 and 50 μm using instruments such as TES. However, the Martian atmosphere contains fine-grained dust and H_2O ice, both of which behave like aerosols, as well as a major CO_2 atmospheric absorption band between 13 and 17 μm (e.g., Smith et al., 2000). In particular, Mars Global Surveyor TES spectrally sampled the planet at both 10 cm^{-1} and 5 cm^{-1} fwhm resolutions (Christensen et al., 2001a) until 2006 when the last contact was made with the spacecraft. TES spectral data were acquired as longitudinal (i.e., north to south) orbital swaths, with ~3 km target footprints along its orbital path (Christensen et al., 2001a). Although not an imaging spectrometer, TES spectral strips have been assembled as hyperspectral image cubes.

Emission Spectrometer (TES) onboard Mars Global Surveyor (MGS) and Thermal Emission Imaging System (THEMIS) onboard Mars Odyssey – Christensen et al., 2001a; 2004] than what exists for Earth at comparable spatial resolutions and continental scales [e.g., Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) – Yamaguchi et al., 1998; Hulley and Hook, 2009; Hulley et al., 2009]. Studies exploiting multispectral remotely sensed data in the TIR (8–14 μm) terrestrial atmospheric window portion of the electromagnetic spectrum are less common, and hyperspectral TIR emissivity data coverage of the Earth is scarce at present. Table 1 compares the spatial and spectral resolution characteristics of notable terrestrial airborne and spaceborne sensors providing TIR emissivity data with those sensors that have orbited around Mars.

Diagnostic absorption features occur over the wavelength region of the fundamental Si-O stretching vibrational modes in the lattice of silicate minerals, generally between 8 and 11 μm (Lyon, 1965; Hunt, 1980; Salisbury et al., 1987). This wavelength region is often referred to as the "reststrahlen bands" (German: "residual rays") and spectral features generally shift from shorter wavelengths for framework silicates—such as quartz and feldspar—to longer wavelengths for mafic minerals [such as olivine, pyroxene and amphibole, which are characterized by sheet, chain or isolated tetrahedral crystal structures (Lyon, 1965; Hunt, 1980; Salisbury et al., 1987)]. Additional and weaker silicate absorption features are situated between 12.0 and 16.7 μm due to bending vibrational modes within (Si,Al)-O-(Si,Al) groups, as well as asymmetric stretching vibrations within carbonates (near 11.4 and 14.3 μm) and sulfates (near 8.7 μm), and O-H and H-O-H bending and stretching modes near 11.0 μm that are exhibited by aluminum-bearing clay minerals (Lyon, 1965; Hunt, 1980; Salisbury et al., 1987). Variations in the shape and intensity of spectral absorption features at TIR wavelengths caused by such processes on the molecular level (as well as additional grain-size effects) helps distinguish silicate minerals from one another in a manner that is typically not possible with VSWIR reflectance data. Many of these minerals and their corresponding lithic and vitric forms can occur as sand-sized sediment mixtures that comprise the bulk of dunes as well as potential alluvial and playa source materials found on Earth as well as Mars (Muhs, 2004; Edgett and Lancaster, 1993; Charles and Titus, 2015).

For Earth, the ASTER instrument onboard NASA's Terra satellite is the highest resolution sensor providing global TIR emissivity data at 90-m spatial resolution, five multispectral bands (Table 1), and an effective revisit period of 16 days that is reducible to 4 days due to its off-nadir pointing capability (Yamaguchi et al., 1998). Future spaceborne missions, such as HyspIRI and ECOSTRESS, will provide regional to global TIR emissivity coverage at better (1) spatial resolutions (e.g., ~60 m for HyspIRI – Table 1), (2) spectral resolutions (e.g., seven emissivity bands in the 8 to 14 μm atmospheric window for HyspIRI – Table 1), and (3) temporal resolutions (e.g., > 5 observations per day with a 4-day revisit period for ECOSTRESS – Hulley and Hook, in press). Improved resolutions such as these will enable construction of better maps of compositional variability, source materials, and changing activity within terrestrial dune systems. Improved terrestrial resolutions will also enable better comparative planetology studies of dune fields on Earth and Mars. Such studies may provide us with a better understanding of how differing source rock compositions and surface processes (e.g., weathering and erosion rates) between the two planets can lead to such similar aeolian landforms (e.g., Edgett and Christensen, 1991; Edgett and Lancaster, 1993).

The purpose of this paper is threefold: First, we use linear deconvolution methods (e.g., Ramsey and Christensen, 1998) to test how well various TIR sensors measuring emissivity in the 8–14 μm terrestrial atmospheric window can resolve proportions of minerals intimately mixed together within various aeolian sand deposits. In the process, we assess the effects of grain-size variability and spectral library limitations by comparing deconvolution modeled mixtures with their original laboratory-measured emissivity spectra. For this aspect of the study, we specifically focus on comparing existing terrestrial airborne hyperspectral sensors (e.g., Sebass, HyTES, and MAKO – Kirkland et al., 2002; Hook et al., 2013) with existing, defunct and future multispectral sensors comparable to or better than the THEMIS sensor that is in orbit around Mars (e.g., ASTER, ECOSTRESS, TIMS, HyspIRI, and MASTER in order of increasing number of spectral bands or decreasing pixel size; Table 1). We focus on eight compositionally distinct dune fields shown in Fig. 1 and listed below. Because global hyperspectral TIR data coverage is expected to remain limited for much of the Earth over the next decade or more, it is important to evaluate the effects of degraded