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Thermophysical properties along *Curiosity*'s traverse in Gale crater, Mars, derived from the REMS ground temperature sensor

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ABSTRACT

The REMS instrument onboard the Mars Science Laboratory rover, *Curiosity*, has measured ground temperature nearly continuously at hourly intervals for two Mars years. Coverage of the entire diurnal cycle at 1 Hz is available every few martian days. We compare these measurements with predictions of surface-atmosphere thermal models to derive the apparent thermal inertia and thermally derived albedo along the rover's traverse after accounting for the radiative effects of atmospheric water ice during fall and winter, as is necessary to match the measured seasonal trend. The REMS measurements can distinguish between active sand, other loose materials, mudstone, and sandstone based on their thermophysical properties. However, the apparent thermal inertias of bedrock-dominated surfaces (~350–550 J m^{-2} K^{-1} s$^{-1/2}$) are lower than expected. We use rover imagery and the detailed shape of the diurnal ground temperature curve to explore whether lateral or vertical heterogeneity in the surface materials within the sensor footprint might explain the low inertias. We find that the bedrock component of the surface can have a thermal inertia as high as 650–1700 J m^{-2} K^{-1} s$^{-1/2}$ for mudstone sites and ~700 J m^{-2} K^{-1} s$^{-1/2}$ for sandstone sites in models runs that include lateral and vertical mixing. Although the results of our forward modeling approach may be non-unique, they demonstrate the potential to extract information about lateral and vertical variations in thermophysical properties from temporally resolved measurements of ground temperature.

1. Introduction

1.1. Background

The Mars Science Laboratory (MSL) mission, with its *Curiosity* rover, reached Mars in August 2012, with the goal of using geological and geochemical analyses to understand the past and present habitability of its field area (Grotzinger et al., 2012). The rover was designed around mobility and the ability to acquire and analyze samples of rock and soil in onboard laboratories. In parallel with these activities, a number of instruments on the rover monitor the modern environment by acquiring systematic meteorological, climatological, and radiation measurements.

The Ground Temperature Sensor (GTS) on *Curiosity*'s Rover Environmental Monitoring Station (REMS) (Gómez-Elvira et al., 2012) provides continual measurements of ground brightness temperature, T_B, that span and resolve the diurnal cycle. This capability follows the pioneering Miniature-Thermal Emission Spectrometer (Mini-TES) instruments on the Mars Exploration Rovers (Christensen et al., 2003; Fergason et al., 2006) that sampled the diurnal cycle, but could be used only sporadically throughout those missions because they required articulation of the rover's mast.

While T_B has been measured from Mars orbit for decades, orbital and *in situ* measurements are quite different in nature. Data from the Thermal Emission Spectrometer (TES) on *Mars Global Surveyor* and from the Thermal Emission Imaging System (THEMIS) on *Mars Odyssey* were acquired at nadir and from above the atmosphere, with footprints of several km and ~100 m, respectively. Those orbiters were sun-synchronous, resulting in measurements that have seasonal and global coverage, but occur only twice per diurnal cycle at most latitudes. The GTS makes measurements at the local scale (~10 m) and at an emission angle of 64°± 20° (for a horizontal surface). The measurements are continual with respect to the diurnal and seasonal cycles, but rover movement means that

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the total data set acquired at any particular location is of limited duration. *Curiosity* has observed many locations for at least one diurnal cycle, but none has been observed for more than a small fraction of a season.

The GTS data provide the opportunity to investigate the properties of surface materials along the rover's traverse based on their radiative and thermal response to atmosphere-moderated solar forcing. The nature of the response is controlled by the solar-wavelength albedo and infrared emissivity of the surface, surface orientation (i.e., slope and azimuth), and thermal inertia, $I = (k\rho c)^{1/2}$ (in units of $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$, omitted hereafter), down to a depth relevant for diurnal or seasonal time scales (typically several cm and a few 10 s of cm, respectively). Of the components within I (thermal conductivity, k, bulk density, ρ, and specific heat capacity, c), the thermal conductivity varies the most within geological materials on Mars (Wechsler et al., 1972). It is a function of particle size for unconsolidated materials at Mars atmospheric pressures (Presley and Christensen, 1997). For consolidated materials (e.g., duricrust, clasts, and bedrock), k varies with composition, porosity, and degree of cementation. These properties are of key interest for understanding the processes of primary deposition, diagenesis, and/or alteration of the sedimentary rocks along *Curiosity*'s traverse.

A complicating factor in analyzing remotely sensed ground temperatures is that the measured radiance is a composite from the mix of materials within the sensor's footprint. Imagery can be used to independently estimate the type and areal coverage of materials such as rock vs. fines (e.g., Putzig and Mellon, 2007a). Also, the thermal response at the surface is determined by the thermophysical properties within the near-surface layer. Depth-dependent thermal or physical properties can influence the shape of the diurnal and seasonal ground temperature profiles, and therefore also can be inferred from those measurements (Putzig and Mellon, 2007b), as demonstrated using diurnal curves of the lunar ground temperature (Vasavada et al., 2012a). As such, there is the potential to use the GTS data as a probe of the subsurface that is otherwise hidden from the rover (Hamilton et al., 2014).

1.2. Previous thermophysical studies of Gale crater

A number of prior studies have used thermal measurements to interpret the nature of surface materials within Gale crater. Studies using TES and THEMIS thermal data and orbiter imagery found *Curiosity*'s landing ellipse and traverse area to have an albedo, A, of 0.2 to 0.25, and an average I of 365, with excursions to ∼500 (Pelkey and Jakosky, 2002; Pelkey et al., 2004; Fergason et al., 2012). Those studies interpreted the albedo to indicate a surface mostly covered by an optically thick but thermally insignificant dust layer. They interpreted the I values to indicate the presence of an indurated surface with occasional unconsolidated materials and exposures of bedrock. They also noted ripples and dunes, including the low-A, low-I sand dunes and sheets along the northern flank of Aeolis Mons (informally called the Bagnold Dunes).

Hamilton et al. (2014) derived surface thermophysical properties from the GTS over the first 100 sols of the mission by fitting ground temperatures over the diurnal cycle with a thermal model. Martínez et al. (2014) also analyzed early mission data, and used a surface energy balance method that yielded similar results. Previous GTS analyses have noted offsets between GTS measurements and model predictions, most notably that the ground warms faster than predicted in the mid-morning and cools more slowly than predicted in the late afternoon (Hamilton et al., 2014; Martínez et al., 2014; Audouard et al., 2016). These offsets are discussed further in Section 5.

1.3. Outline of this study

In this study we use the GTS and other data sets from *Curiosity* to derive the thermophysical properties of the surfaces traversed by the rover from landing through the 1337th sol (martian day) of the mission, spanning two Mars years. We first use the diurnal curve of T_B measured each sol to derive the apparent I and thermally derived albedo, A_T, for the location of the GTS footprint. The apparent I and A_T are derived from the composite radiation received at the sensor from the mix of materials within the footprint and may not be precisely relatable to any of the actual materials present. But these results allow for a direct comparison with orbit-based derivations that also measure the composite radiation, while having the benefit of additional interpretation from rover-scale imagery.

We then focus on locations where the rover was stationary for several sols. When a data set spans multiple sols, the local time covered with 1-Hz sampling is greater, and the accuracy at a given local time can be improved by averaging across sols. These locations are chosen such that they are representative of the major surface types encountered along the traverse, such as sand, gravel, mudstone, and sandstone (Grotzinger et al., 2014; 2015; Vasavada et al., 2014). We use rover imagery and the detailed shape of the diurnal curve at each site to explore the effects of lateral and vertical heterogeneities of materials in the GTS footprint. The resulting spatially differentiated values of I and A_T can be physically related to thermal and physical properties of particular materials.

2. Data and methodology

2.1. REMS data set

The REMS instrument suite measures atmospheric pressure, air temperature, ground temperature, relative humidity, wind speed, wind direction, and ultraviolet radiation using sensors distributed on two short booms attached to the rover's remote sensing mast, on the rover's top deck, and inside its chassis (Gómez-Elvira et al., 2012, 2014). Ground brightness temperature measurements are made by the GTS (Sebastián et al., 2010; 2011), consisting of three thermopile-based pyrometers located on one of the booms. These sensors view the martian surface 122° to the right of the forward direction of the rover from a height of ∼1.6 m. The field of view (FOV) of each is 63° (horizontal) by 40° (vertical). If the rover were on a horizontal surface, the FOV would be centered 26° below the horizon and project over a surface area of ∼100 m^2, spanning ∼1.5 m to 15 m in distance from the rover's mast. The footprint was designed to be relatively large to avoid small-scale variability due to rocks, roughness, and shadows, and to diminish the thermal influences of the rover's Radioisotope Thermoelectric Generator (RTG) and the rover's shadow.

Radiance is collected in three bandpasses, but only the 8–14 µm channel meets the design requirement to retrieve ground brightness temperature with a resolution ≤ 2 K and an accuracy ≤ 10 K from 150 to 300 K. This requirement is met when measurements are averaged over at least 1 min and when the ASIC temperature (in the boom electronics) is above 223 K (Gómez-Elvira et al., 2012). The GTS includes an active self-calibration system to compensate for potential degradation during the mission due to dust collecting on the sensor window.

Ground brightness temperature measurements are acquired at 1 Hz for 5 min at the beginning of each "hour" (in Mars Local Mean Solar Time, LMST), with an hour representing 1/24 of a sol. Several of the hourly sessions in each sol are extended to a full hour, with the specific hours chosen such that the entire diurnal cycle is resolved at 1 Hz every few sols (Gómez-Elvira et al., 2014).