Analysis of a thermal correction method for the MIRS infrared spectrometer: preparation for the future observations of the Martian moons Phobos and Deimos

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Introduction: The Martian Moon eXploration (MMX) mission is scheduled to be launched to the Martian system in 2024 [1]. The scientific payload will include the MMX InfraRed Spectrometer (MIRS, [2]), an instrument dedicated to the study of Mars and its satellites: Phobos and Deimos. MIRS data will contribute, together with the other instruments and the sample return analysis, to understand the origin of the two Martian moons. It will help to decipher whether they are captured asteroids or rather formed by accretion from a debris disk, the latter resulting from a giant impact between Mars and a planetesimal. In the spectral range covered by MIRS (0.9-3.6 µm), several components of geological interest will be studied through their spectral properties such as anhydrous and hydrous silicate minerals, water ice, or organic matter. Constraining the presence and relative abundance of these phases will help to determine the Martian moons' formation processes. However, several absorption bands associated with these compounds are in the spectral region beyond ~2.5 µm, where the signal collected by the instrument is a combination of reflected sunlight and thermal emission from the observed surfaces. The thermal emission - the so-called thermal tail - can strongly modify the continuum of the spectra and the width of the absorption bands. Consequently, before proceeding to the mineralogical analysis and interpretation of future MIRS data, a thermal emission correction is needed. In this study, a simple method of thermal emission correction is tested on synthetic data to evaluate its potential and limitations.

Method: The thermal tails of spectra are mainly controlled by the surface's temperatures, roughness and emissivity. For airless bodies, such as Phobos and Deimos, the surface conditions can be highly fluctuating, between ~130 K and ~300 K [3]. Temperature and emissivity are often not well-constrained on planetary surfaces, but they can be estimated directly from the infrared spectra. In this work, we deliberately explored a simple empirical method of thermal tail removal, based on Planck blackbody fit, owing to the MIRS instrument will provide a large amount of data and a method running quickly will save computing time and make it easier data interpretation during MMX flight operations. We used the approach from [4], which was originally developed to correct the Moon Mineralogy Mapper (M^3) observations onboard the Chandrayaan-1 spacecraft. This approach is iterative and uses the assumption that the continuum of the reflected solar component is approximately linear beyond 2.5 µm. The signal at short wavelengths (with no thermal contribution) is used to extrapolate the reflected component in the thermal tail part of the spectra at a given wavelength. The differences between the projected reflectance and the original spectra, corresponding to the thermal contribution, are then fitted with a blackbody Planck function radiation, and a temperature can be derived. Emissivity (ε) is determined by using the projected I/F (the signal collected by the instrument normalized to the solar flux) at a specific wavelength and Kirchhoff's law ($\varepsilon=1-I/F$). Here, we perform two iterations to adjust the temperature, using in the second run the previous corrected spectra. While in the first iteration, emissivity is considered as constant with wavelength, the second iteration will consider a wavelength-dependent emissivity (i.e., the Kirchhoff's law is used for each wavelength).

Synthetic data: Different spectral datasets were generated for the purpose of this study by means of a thermophysical model [5], which calculates thermal infrared spectra of airless bodies or sub-portions thereof as a function of several physical parameters such as albedo, roughness, thermal inertia, rotation period, direction of the rotation axis, as well as illumination and viewing geometry. The first dataset corresponds to seven synthetic reflectance spectra thought to be reasonably analogous to Phobos, for which thermal contribution at different temperatures from 262 K to 329 K has been added. In this first set of simulations, the scene corresponds to a flat facet of the Phobos shape model in nadir view. The second dataset includes the same parameters but this time, roughness has been generated by adding hemispherical section craters into the facet. This makes such that sub-facets with different inclinations with respect to the sun and the instrument compose the field of view. Each sub-facet contributes to the thermal infrared flux with its own temperature, which depends on the geometry relative to the sun. Finally, the last dataset is similar to the previous one but includes a fictitious absorption band centered at 3.2 µm, to study its effect on thermal correction. In all our simulations, ε has been set to 0.9, which is thought to be consistent with the Martian moon surfaces.

Results: The first dataset is used to test the consistency between the temperature retrieved by the thermal correction model and the temperature used as input by the thermophysical model. Our results show that the first iteration gives an average of ~0.8 K of difference from the true temperature, while the second iteration increases the error on temperature retrieval with an average of ~1.4 K of difference. These results are consistent with the experiment made by [4], who found that the derived temperature by this approach of heated basalt in the laboratory was around 1 degree of the true measured temperature. The emissivity predicted by the model is also very consistent with the one used in the thermophysical model ($\varepsilon=0.9$) to generate the data. The first iteration predicts ε~0.88 for all temperatures, whereas the second iteration predicts emissivity within 0.86-0.88. To determine the efficiency of the thermal correction, we calculated the mean absolute percentage error (MAPE), which quantifies the difference between each corrected spectrum and its spectrum of reference (i.e. spectrum generated without thermal contribution) that can be expressed as MAPE = $\sum_{\lambda>2.5\,\mu m}^{n} \left|\frac{y_\lambda - x_\lambda}{y_\lambda}\right| \frac{100}{n}$, where y_λ and x_λ are the I/F values of the reference and corrected spectra for each wavelength in the thermal part (i.e., λ>2.5 µm). For the first data set, we found that corrected spectra have respectively MAPE scores of ~1.25% (σ=0.5 %) and ~0.21% (σ=0.2%) on average for the first and second iterations, which is pretty good. For the second dataset, including roughness in the simulated scene, the complexity of the data slightly degrades the thermal correction (Figure 1, left panel). For all spectra, a small rise in reflectance can be observed after the thermal correction at the edge of the spectra due to an under-correction. Nevertheless, this residual thermal contribution is quite negligible as expressed by the good MAPE scores. On average, they are respectively equivalent to ~3.1% (σ=1.1%) and ~1% (σ=0.49%), for the first and second iterations, which is satisfying. Emissivity predicted by the model ($\varepsilon_{\text{iteration 1}}$~0.88, $\varepsilon_{\text{iteration 2}}$= 0.86-0.88) is still very consistent with the reference and is similar to the emissivity guessed for the first dataset.

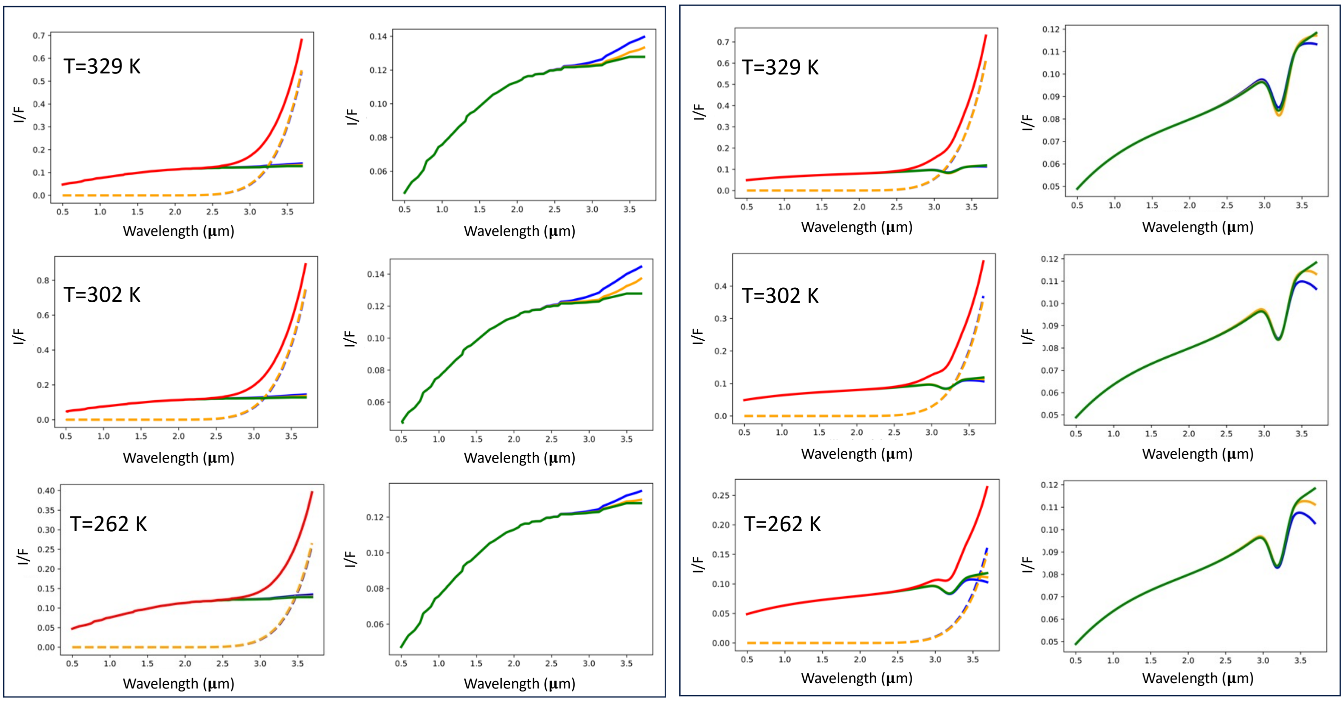

Figure 1. Results of thermal correction of several synthetic reflectance spectra of Phobos generated by means of a thermophysical model [5]. Spectra with thermal emission (red lines) are compared to the two iterations of thermal removal (first and second iterations are represented respectively in blue and orange). Green spectra correspond to the synthetic spectra simulated without the thermal contribution and they serve as a benchmark. Dash lines correspond to the Planck functions of the first and second iterations (respectively in blue and orange). The left panel shows the results for the second set of synthetic data, whereas the right panel corresponds to the third dataset with absorption bands.

For the synthetic spectra containing a synthetic absorption band at 3.2 µm, the model of thermal correction seems to be still efficient (Figure 1, right panel). The MAPE scores of these spectra remain quite good with an average of ~1.6% (σ=0.61%) and ~0.8% (σ=0.01 %). Emissivity is still overall in line with the one used to generate the data ($\varepsilon_{\text{iteration 1}}$~0.92, $\varepsilon_{\text{iteration 2}}$=0.89-0.92). Despite the relatively good MAPE scores, a drop in reflectance can be observed at the edge of the spectra (beyond 3.45 µm), which was also observed in the work made by [4]. In terms of band depths, the differences with the references are in averages respectively equivalent to ~7.3% (σ=0.96%) and ~4.7% (σ=4.2%) for spectra corrected with one and two iterations.

Conclusion: In this study, we tested on simulated data of Phobos, the thermal correction method developed by [4]. Our results show that this method appears to be usable for the thermal correction of future MIRS observations. The correction seems to be efficient, especially for high surface temperatures. Moreover, by improving each time the MAPE scores with the second run of the data treatment, we confirmed the efficiency of the iterative approach. We also quantified the impact of the thermal correction on the absorption bands and found an overestimate of the band depths limited to a few percent. This is an ongoing work to improve the thermal tail removal in preparation for the planned activity of MIRS during the orbital phase of MMX mission.

References: **[1]** Kuramoto, K., et al., (2021), Earth Planets Space. 74(1), 1-31. **[2]** Barucci, M. A., et al., (2021), Earth, Planets, and Space. 73-211. **[3]** Giuranna, M., et al. (2011), Planetary and Space Science. *59*(13), 1308-1325. **[4]** Clark, R. N., et al., (2011), Journal of Geophysical Research: Planets, 116(E6). **[5]** Delbo, M., et al., (2015), Asteroids IV, 1, 107-128.