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EXPLORING THE TRANSMISSION OF VNIR LIGHT THROUGH MARTIAN REGOLITH

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ABSTRACT

The identification and analysis of hyperspectral visible and near-infrared signatures of key targets, notably silica-rich outcrops, on Mars can be considerably affected by the presence of covering regolith materials. Before reaching and after being reflected by these targets, the impinging electromagnetic radiation is propagated through the regolith materials. Hence, the investigation of these materials' light transmission capabilities, the focal point of this work, can be instrumental for the correct interpretation of the hyperspectral responses of silica-rich deposits and other subsurface targets. In the absence of actual Martian regolith samples to be used in transmittance experiments, high-fidelity modeling approaches can effectively contribute to advance the knowledge in this area. Accordingly, we carried out a controlled assessment of the quantitative and qualitative traits of light transmitted through representative samples of Martian regolith using a first-principles simulation framework supported by radiometric data acquired in the Gusev crater on Mars. We also examined changes in the light transmission profiles of Martian regoliths caused by environmentally-induced variations in their grains' morphology.

***Index Terms*—** Mars, regolith, silica-rich deposits, light propagation, hyperspectral signatures, predictive simulations.

1. INTRODUCTION

The occurrence of hydrated silica-rich deposits on Mars is central in studies involving the planet's evolutionary history and habitability [1]. Moreover, it has relevant astrobiological ramifications since these materials may provide mechanisms for preserving evidence of subsurface life [2, 3]. For these reasons, regions that may contain silica-rich deposits are considered suitable candidates for landing sites of rover-based missions, including those aimed to collect soil samples to be returned and analyzed in laboratories worldwide [4, 5].

Widespread outcrops of hydrated silica have been identified in a variety of ancient aqueous environments on Mars using hyperspectral visible and near-infrared (VNIR) data acquisition technologies [1, 5]. Silica-rich materials may be present in depths from a few hundred micrometers to several centimeters [4]. They are often covered by sand-textured regolith [6] characterized by the presence of iron oxides such as hematite, magnetite and goethite, which has been connected to aqueous activity on Mars [7].

Accordingly, for observations in the visible to near-infrared spectral domain aiming at detecting, mapping and interpreting the entangled presence of iron-oxides and silica-rich materials in Martian soil, it becomes essential to appropriately account for the presence of sand-textured regolith affecting the propagation of light to and from subsurface silica deposits [2, 4, 8, 9]. To the best of our knowledge, however, the light transmission properties of Martian regolith have not been the object of in-depth investigations to date.

In this paper, we aim to make inroads towards addressing this research gap. Since actual samples of Martian regolith are still not available for performing laboratory-based transmittance experiments, their effects on light propagation is often accounted for using models (*e.g.*, [2, 8]) that overlook pivotal aspects related to the particulate nature of Martian regolith as well as the morphology and mineralogy of its grains. In our investigation, we employed a first-principles simulation framework that explicitly accounts for these aspects. Moreover, to ensure the fidelity of its predictions, we employ as baseline references for our simulations radiometric data acquired *in situ* using a multispectral camera onboard the Spirit rover deployed at the Gusev crater on Mars [8].

The light propagation properties of regolith and hydrated silica materials in the VNIR domain are sensitive to past and present environmental conditions [1]. These include extreme aeolian events, like sand storms and dust devils, capable of affecting the morphology of these materials' constituent grains [6, 10] and, consequently, their interactions with impinging light. For example, the transportation of regolith grains by wind may involve rolling, suspension and saltation processes [11]. In the latter, the grains are temporarily suspended by the wind before impacting the soil surface [12, 13]. Increasing rigor in the last stage of transportation can increase grain fracturing and chipping. This, in turn, can lead to grains with a rougher surface and a more spherical shape [11].

Hence, the understanding of these interconnections is also relevant for the identification and correct interpretation of hyperspectral signatures originating from hydrated-silica outcrops on Mars [1]. For this reason, during our investigation,

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we also examined environmentally-induced variations on the morphological characteristics of regolith grains, and the impact of these variations on light transmission.

2. MATERIALS AND METHODS

In our investigation, we considered samples of regolith covering two sites located in the Gusev crater [8], henceforth referred to as B (bright) and D (dark). In order to characterize these samples, we have employed data specific to Martian sand-textured soils whenever such data was available (*e.g.*, porosity (60%) [14]), and average data describing terrestrial sand-textured soils (*e.g.*, grain roundness (0.482) and sphericity (0.798)) otherwise [14, 15]. We note that while a high roundness value corresponds to a smooth grain [11], a high sphericity value indicates a grain with a geometry close to that of a sphere [17]. The remaining parameter values used to obtain the modeled hyperspectral data are given in Table 1. It is also worth mentioning that the percentages of the sand-sized and silt-sized particles depicted in Table 1 are employed to compute the dimensions of the samples' grains using a particle size distribution provided by Shirazi *et al.* [16].

Sand-textured soils are primarily composed of grains (particles) of weathered rocks immersed in a pore space. These rocks correspond to the parent (core) material of these soils. Depending on the weathering process, the core material may occur as pure particles, coated particles or mixed with contaminants [17]. The particle coatings correspond to a mineral (*e.g.*, illite) matrix [17]. The contaminants often include iron oxides (*e.g.*, hematite, goethite and magnetite), which may also occur as pure particles or embedded in the particle coating. For the purposes of our investigation, we considered basalt as the core material of pure and coated Martian regolith grains, and a silica-rich basaltic composition occurring as the core material of the mixed grains [15].

Table 1. Parameter values used to characterize the two Martian regolith samples selected for this investigation. The texture of the samples is described by the percentages ($\%$) of sand (s_a) and silt (s_i). The particle type distributions considered in the simulations are given in terms of the percentages ($\%$) of pure (μ_p), mixed (μ_m) and coated (μ_c) grains. The parameter r_{hg} corresponds to the ratio between the mass fraction of hematite to ϑ_{hg} (the total mass fraction of hematite and goethite). The parameter ϑ_m represents the mass fraction of magnetite, which is assumed to appear as pure particles [14].

Samples	s_a	s_i	μ_p	μ_m	μ_c	r_{hg}	ϑ_{hg}	ϑ_m
B	90	10	10	90	0	0.25	0.045	0.01
D	92.5	7.5	10	80	10	0.5	0.035	0.02

Our controlled *in silico* experiments consisted in the computation of directional-hemispherical reflectance and transmittance curves using a virtual spectrophotometer [18] and an enhanced implementation of the first-principles light transport model originally known as SPLITS (*Sp*ectral *Li*ght *T*ransport Model for *S*and) [17, 19]. Each spectral curve was obtained by casting 10^6 rays (per sampled wavelength) onto the samples. Unless otherwise stated, the modeled curves were computed considering an angle of incidence of $0°$ and a spectral region from 435 to 1000 nm for consistency with the radiometric data [8] used as baseline references for our simulations. To enable the reproduction of our findings, we have made the enhanced implementation of SPLITS, termed SPLITS-2 [19], available online [20] along with its supporting spectral datasets (e.g., refractive index and extinction coefficient curves).

For the baseline reflectance computations, we considered the samples' thickness equal to 1 m, a default value that guarantees depth-invariant readings [21]. For the transmittance experiments, we considered thickness values on the order of a millimeter. This enabled us to assess variations on the penetration of impinging light before its attenuation resulted in (small) values with an uncertainty (precision) below that observed in actual measurements [18, 21].

3. RESULTS AND DISCUSSION

Initially, we computed reflectance curves for the selected regolith samples. We then compared these curves with those obtained *in situ* [8] in order to assess the plausibility of our choice of characterization parameters (Table 1). As it can be observed in Fig. 1, the values chosen (from physically-valid ranges) for the parameters resulted in a close qualitative agreement between the modeled and measured curves. Moreover, considering that the latter were estimated to be within 5 to 10 $\%$ absolute accuracy [8], and the fact that not all minerals found in the Gusev crater sites could be accounted for in the simulations due to the lack of reliable supporting data, the level of quantitative agreement between the curves further reinforced the plausibility of our baseline datasets.

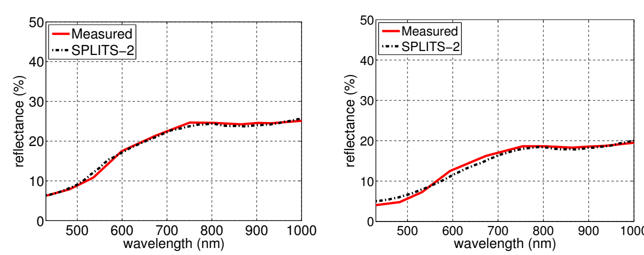

Fig. 1. Comparison of measured [8] and modeled (using the SPLITS-2 model) reflectance curves obtained for the selected Martian regolith samples B (left) and D (right).

Subsequently, we performed the transmittance experiments. The results presented in Fig. 2 depict a nonlinear decrease in the samples' transmittance as their thickness is increased. However, one can observe just minor variations in the rate of transmittance decrease as light penetrates deeper in the samples. One can also observe that the transmittance values are higher at the longer wavelengths. This may be attributed to the presence of the iron oxides and their relatively low extinction coefficients at those wavelengths.

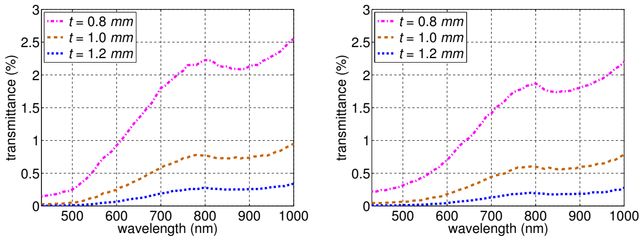

Fig. 2. Comparisons of modeled transmittance curves obtained for the selected Martian regolith samples, B (left) and D (right), considering distinct values for their thickness (t).

The curves presented in Fig. 2 also show that, for a thickness of 1 mm, less than 1% of the impinging light is transmitted through the regolith samples. This indicates that less than 0.01% of the light reflected by a subsurface target covered by a 1 mm thick layer of these regoliths would be detected (within the spectral region of interest) after being transmitted through these particulate materials. This quantitatively demonstrates how the presence of sand-textured regolith may represent a major hindrance for the reliable remote identification and analysis of biophysical signatures from subsurface targets.

We then proceeded to examine the angular dependence of the light transmitted through the regolith samples. Accordingly, we varied the angle of incidence of the impinging light with respect to the samples' normal vector. The graphs presented in Fig. 3 depict the resulting changes in transmittance for three selected wavelengths. As expected, the transmittance values decrease as the angle of incidence is increased since the probability of absorption tends to increase following the resulting accentuation of light detour effects. However, our experiments indicate that the rate of change is not linear. More specifically, more accentuated changes were observed for angles of incidence between $\approx 20°$ and $\approx 60°$, and for the shortest selected wavelength. This suggests that the detection of biophysical signatures from subsurface targets would be even more difficult under these angular and spectral light incidence conditions.

Lastly, we performed experiments to assess the sensitivity of the light transmission profiles to variations on the sphericity of regolith grains. We remark that these variations can be associated to the different processes affecting the grains' transportation, notably extreme aeolian events. As it can be observed in the graphs presented in Fig. 4, a decrease in the grains' sphericity leads to a reduction in the regolith samples' transmittance. Again, the rate of change is not linear, with more accentuated transmittance reductions being observed for lower sphericity values. This suggests that regolith deposits formed by extreme aeolian events, which can increase the grains' sphericity [11], are more likely to have stronger light transmission capabilities than deposits (with similar mineralogical characteristics) formed by water-transported grains. Consequently, the latter, which may have been formed in various locations at multiple times in the geological history of the Gusev crater [6], would be more likely to mask the biophysical signatures from subsurface targets.

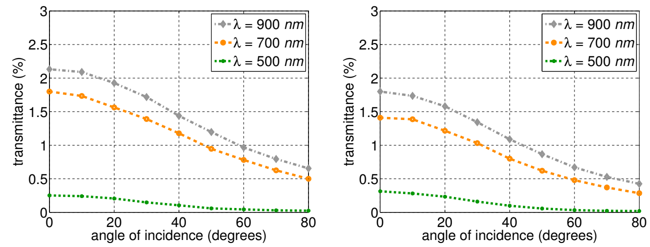

Fig. 3. Graphs depicting the angular dependence of modeled transmittance curves obtained for the selected Martian regolith samples, B (left) and D (right), considering three representative wavelengths (λ) and a thickness of 0.8 mm.

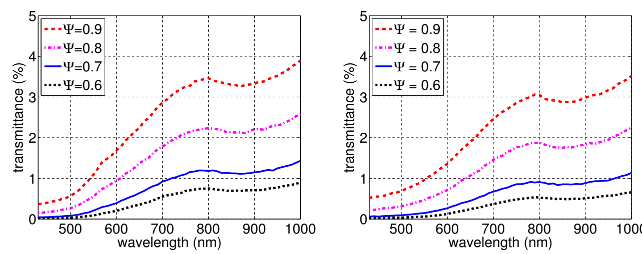

Fig. 4. Comparisons of modeled transmittance curves obtained for the selected Martian regolith samples, B (left) and D (right), considering distinct values for the average sphericity (Ψ) of their grains and a thickness of 0.8 mm.

It is worth mentioning that we also performed experiments to assess the sensitivity of the light transmission profiles to variations on the roundness ("smoothness") of regolith' grains. The outcomes of these experiments resulted in negligible changes in the transmittance curves in comparison with the results of our previous experiments. Thus, for conciseness, the corresponding graphs are not provided here.

4. CONCLUSION

In this paper, we have examined the light transmission profiles of selected samples of sand-textured Martian regolith. Our findings show that these profiles exhibit a non-linear dependence not only on light incidence conditions, but also on the morphological characteristics of the regolith samples' constituent grains, which are directly associated with the geological origins of the samples as well as environmental events.

Moreover, our findings indicate that these materials can have a relatively high impact on the identification and analysis of biophysical signatures from subsurface targets in the VNIR spectral domain. Accordingly, the ubiquitous presence of these particulate materials on the Martian surface should be properly taken into account in future investigations involving these signatures and their astrobiological implications.

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