CONSTRAINING ROUGHNESS AND THERMAL INERTIA OF PLANETARY SURFACES: A STATISTICAL MULTI-FACET APPROACH.

A. Raponi, M. Formisano, M. Ciarniello, F. Capaccioni, G. Filacchione, M.C. De Sanctis.
Istituto di Astrofisica e Planetologia Spaziali (IAPS), Istituto Nazionale di Astrofisica (INAF), Rome, Italy. (andrea.raponi@inaf.it).

Introduction: The investigation of the thermal properties of planetary surfaces is usually performed studying the variation of the surface temperature as a functionof solar local time. Although thermal emission can be retrieved by infrared spectrometers, the inferred temperature is the result of a best-fit with a black/gray-body model with certain assumptions. Many authors pointed out that neglecting the non-spatially-resolved surface roughness would bring unreliable results (e.g. [1]). This is because asperities of the terrain i) produce shadows, ii) trigger the self-heating, and iii) vary the mean effective incidence and emission angles. The intensities of those effects depend on the mean slope of the asperities, and the viewing geometry and could be relevant at spatial scales smaller than the pixel's size.

Here we show an integrated approach in which thermal inertia can be retrieved from the observed thermal emission by taking advantage of a preliminary photometric analysis of the terrain, applying the multi-facet approach proposed in [2, 3], to constrain the non-spatially-resolved roughness of the surface.

Thermal inertia is usually derived following temporally-based approaches. Here we show an approach in which it can be retrieved performing a spatially-based analysis, thus greatly simplifying the process.

Data: The approach here discussed requires spectral radiance data from infrared imaging spectrometers, which offer the advantage to provide a large spatial statistics of the surface under investigation. In particular, it requires spectral data encompassing the 1-5 µm spectral range from which it would be possible to decouple the solar reflectance contribution (prevalent in the 1-3 µm range) from the thermal emission of the target (steadily increasing from 3 to 5 µm) According to [2, 3] the method requires the following conditions i) the terrain under investigation should have a low albedo (geometric albedo lower than 0.10 - 0.15); ii) the signal coming from different portion of the terrain should be acquired at the same time and at the same phase angles (the maximum allowed difference must be not larger than a few degrees).

All high-spatial-resolution images and hyperspectral data obtained by recent space missions, like ESA/Rosetta to comet 67P and NASA/Dawn to dwarf planet Ceres, comply with these requirements, along with many past and future data from dark asteroids and moons of the solar system (including Earth's Moon).

Method: The objective of the multi-facet approach is to constrain the surface roughness [2, 3] by modeling the distribution of slopes (θ) of the non-spatially resolved asperities of the surface. We remark that the model is capable to handle many possible distribution of slopes, based on a combination of two or more populations of slope distribution, each one modeled following Hapke theory [4]. One specific example is shown in Fig.1.

Once the distribution of slopes has been inferred from data, the same statistical properties of the terrain are adopted to run simulations with a numerical model in COMSOL Multiphysics (www.comsol.com). This model generates rough surfaces by summing trigonometric functions like a Fourier series expansion. Each term of the sum represents a certain frequency of oscillation through space. See Fig. 2 for examples of terrains produced with our model with different roughness, i.e. different values of the mean slope ($\boldsymbol{\theta}$).

We report in Fig.3 an example of surface temperature distribution map as a function of time, assuming this surface is located at the lunar equator.

The model is based on a 3-D finite element method (FEM) which takes into account also for the indirect light, the so-called self-heating (e.g. [5]) which can represent an important energy contribution in rough surfaces.

By varying free parameters (e.g. thermal inertia, albedo) we produce surface temperature distribution maps as a function of time.

Each solution corresponds to a given integrated thermal emission coming from the N non-spatially resolved facets, at the acquisition time of the target data, as discussed in [3]. Thus, thermal inertia can be constrained by comparing modeled and observed thermal emission.

Conclusions: The approach here discussed allow for reliable retrieval of thermal properties of the surface, given the constraints on the non-spatially resolved roughness obtained from the multi-facet algorithm [2, 3].

Thanks to the full exploitation of the data (VNIR for the photometric analysis of the roughness and IR for the thermal emission analysis), a single acquisition from recent imaging spectrometers operating from space missions can provide a local estimate of those properties. The assumption required by this method is that all sampled points of the region under investigation have the same physical properties, which is reasonable when they are spatially close.

Global maps of roughness and thermal inertia can be achieved by applying the method here proposed over many local regions of the target planetary body.

References:

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[3] Raponi et al. (2022) EPSC2022-547, https://doi.org/10.5194/epsc2022-547, 2022.
[4] Hapke B. (1993) Theory of Reflectance and Emittance Spectroscopy.
[5] Formisano M. et al. (2019), *JGR*, 123, 9.

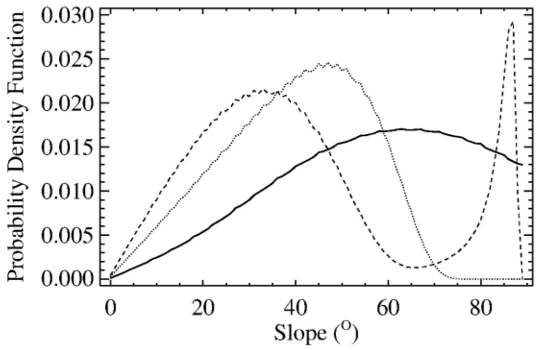

Figure 1. Examples of the outcome of the multi-facet algorithm [2, 3]: distribution of slopes of a single population with $\boldsymbol{\theta}$ = 35° (dotted) as modeled in Hapke [4]; two mixed population with $\boldsymbol{\theta_1}$ = 25°, $\boldsymbol{\theta_2}$ = 85° and weights 0.8 and 0.2 respectively (dashed); population of facets distributed according to $\boldsymbol{\theta_1}$ = 25°, each facet having in turn a certain roughness characterized by $\boldsymbol{\theta_2}$ = 65° (solid bold line).

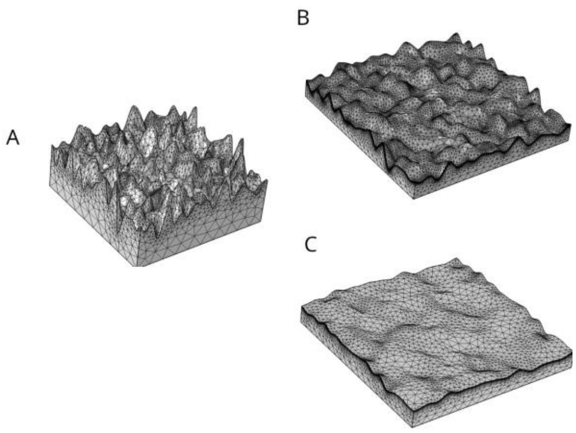

Figure 2. Type of terrains with different roughness produced with our COMSOL model. All terrains reproduce the modeled sub-pixel roughness. Panel A: high roughness ($\boldsymbol{\theta}$ = 60°). Panel B: medium roughness ($\boldsymbol{\theta}$ = 35°). Panel C: low roughness ($\boldsymbol{\theta}$ = 18°).

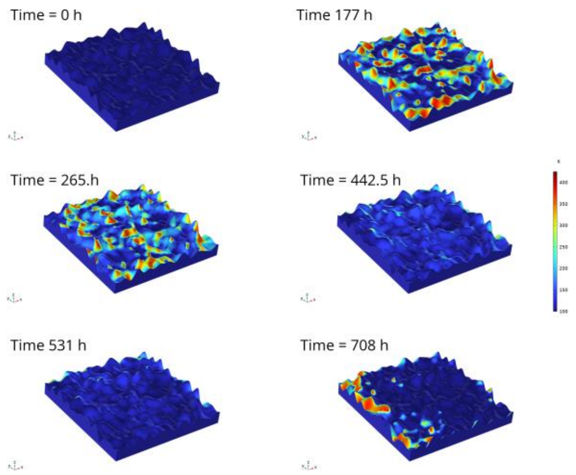

Figure 3. Temperature maps for lunar terrain with $\boldsymbol{\theta}$ = 35°, at the equator, during a revolution. We fix the thermal inertia at 100 TIU (Thermal Inertia Units) and albedo at 0.1.